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Kenneth N. Weaver, Director

REPORT OF INVESTIGATIONS NO. 43

**HYDROGEOLOGY, DIGITAL SOLUTE-TRANSPORT
SIMULATION, AND GEOCHEMISTRY OF THE
LOWER CRETACEOUS AQUIFER SYSTEM
NEAR BALTIMORE, MARYLAND**

by

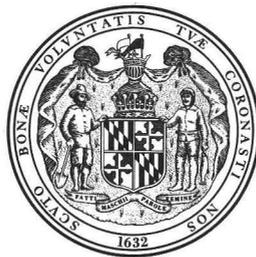
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With a section on

WELL RECORDS, PUMPAGE INFORMATION, AND OTHER SUPPLEMENTAL DATA

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**Prepared in cooperation with the
United States Department of the Interior
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ABSTRACT

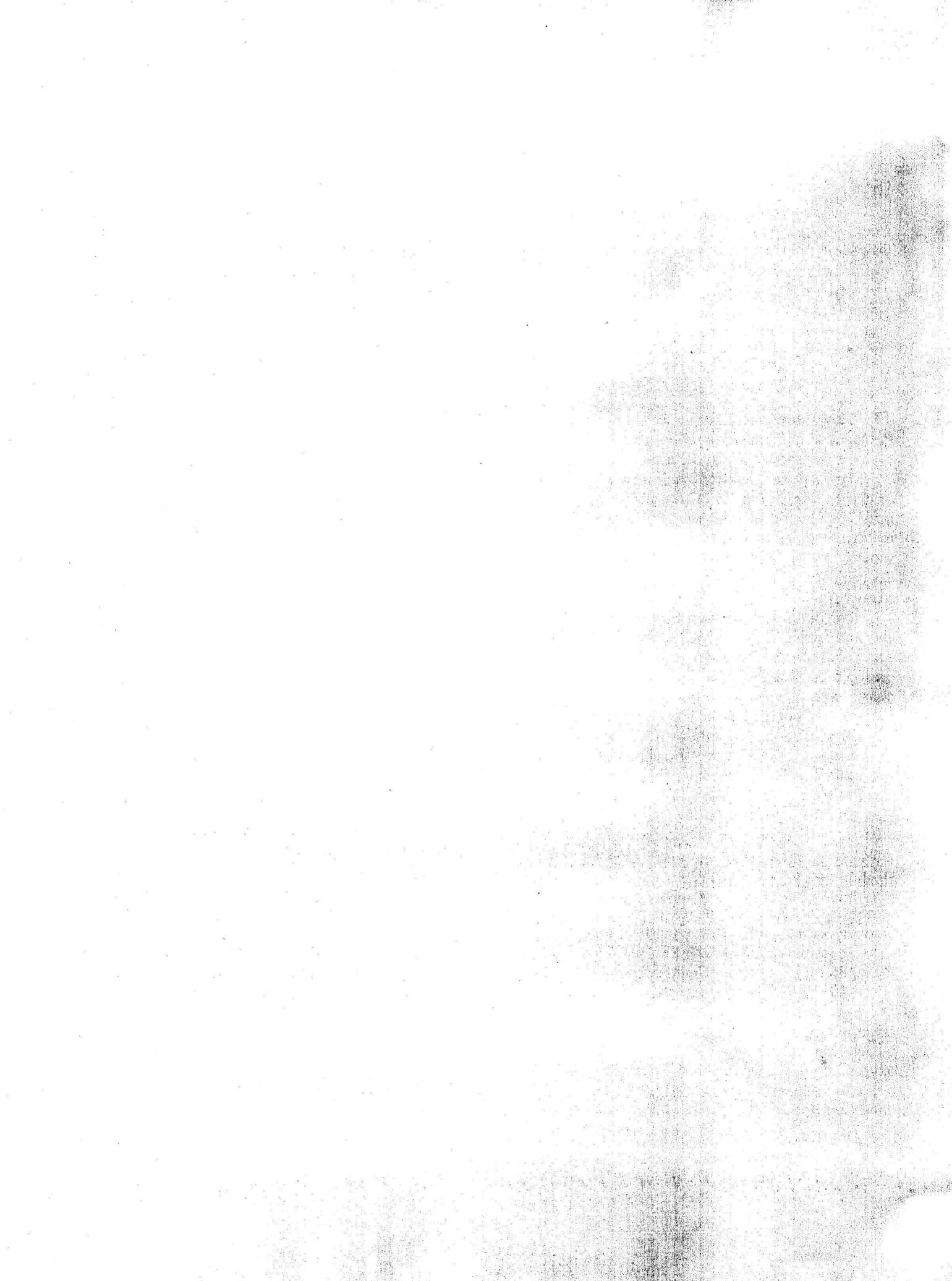
This study was made to develop information on the hydrogeology and ground-water geochemistry of the Patuxent and Patapsco aquifers (Lower Cretaceous) near Baltimore, Maryland. This information is needed to evaluate the availability and chemical quality of water from these aquifers.

The Patuxent aquifer unconformably overlies Lower Paleozoic and Precambrian basement rocks and consists primarily of medium- to coarse-grained quartz sand. Discontinuous lenses of gravel and silty clay are commonly interbedded with the sand-sized material. The Patuxent aquifer in this area attains a thickness of 250 feet and transmissivities range from 2,000 to 8,000 feet squared per day. The Patuxent is the most productive source of ground water in the Baltimore area. In 1982, approximately 11 million gallons of water per day was produced from this unit. Several cones of depression, ranging from 30 to 50 feet below sea level, have developed in response to this pumping stress.

The Arundel Formation conformably overlies the Patuxent aquifer. The Arundel is composed predominantly of clay and ranges from 0 to 150 feet thick. The Arundel exhibits very low vertical hydraulic conductivities that are on the order of 10^{-9} to 10^{-11} feet per second. This unit acts as the upper confining bed of the Patuxent aquifer in much of the project area. The Patapsco aquifer unconformably overlies the Arundel Formation and is a medium- to fine-grained quartz sand. The Patapsco functions as a water-table aquifer in much of the project area. Although the Patapsco has been heavily pumped in the past, pumpage from that aquifer in Baltimore was negligible in 1982.

Brackish-water contamination of the Patuxent and Patapsco aquifers has been a major water-quality problem since the early 1900's. The Patuxent aquifer presently (1982) contains a circular plume of brackish-water contamination about 5 miles in diameter. This plume is centered on the Harbor district and has enlarged measurably since 1945. The Patapsco aquifer has a smaller zone of brackish-water contamination that has decreased in size since 1945. Borehole data demonstrate that the Arundel Formation has been breached by Pleistocene river channels near the Harbor district. These erosional channels provide a conduit for brackish water to intrude into the Patuxent aquifer. A two-dimensional areal solute-transport model of the Patuxent aquifer was constructed. This model was designed to estimate the future movement of the brackish-water plume based on alternative scenarios of aquifer use. Model simulations suggest that the plume will remain relatively immobile if 1982 pumping patterns continue into the foreseeable future. However, increased pumpage in the Marley Neck peninsula could draw the plume to the southeast and increase contamination of the Fairfield area.

The water quality of the Patuxent aquifer is extremely variable. Because of this variability, it is useful to divide the aquifer into three water-quality zones: *Zone 1* — This zone corresponds to the plume of brackish-water contamination. *Zone 2* — This zone exhibits evidence of urbanization-related contamination such as measurable concentrations of organic chemicals and elevated concentrations of trace elements and total organic carbon. *Zone 3* — Water composition in this zone is controlled exclusively by naturally occurring chemical processes. These processes are dominated by reactions involving dissolved iron. Near the outcrop area, oxidation of pyrite and lignite consumes dissolved oxygen and produces ledges of iron hydroxide-cemented sandstones and conglomerates. The predominant dissolved iron species in oxic water is $\text{Fe}(\text{OH})_2^+$. Downgradient, the water becomes anoxic and sulfate reduction becomes an important process. The predominant dissolved iron species in anoxic water is Fe^{2+} .



INTRODUCTION

An abundant supply of fresh ground water is an important asset to industrialized areas. In the Baltimore, Md., area, ground water produced from sediments of Lower Cretaceous age contributed to rapid industrial growth during the 19th and early 20th centuries. Continued industrial activity will require an understanding of the occurrence, movement, and chemical quality of subsurface water resources.

PURPOSE AND SCOPE

The purpose of this report is to provide planners, elected officials, business leaders, engineers, and individual citizens with information on the availability and chemical quality of ground water from the Lower Cretaceous Patuxent and Patapsco aquifers in the Baltimore area.

The first section of this report deals with the physical geology, sedimentary history, and hydrogeology of the Lower Cretaceous sediments in the Baltimore area. Information on aquifer and confining-bed lithology, areal distribution, stratigraphy, water levels and pumping history has been assembled and presented. This information will be useful to engineers, geologists, and well drillers interested in the practical aspects of siting wells.

The second section of this report describes a quantitative evaluation of brackish-water intrusion into the Patuxent aquifer. This intrusion is a major water-quality problem in the Baltimore area. The movement of brackish water in response to pumping stresses is an important consideration of future aquifer use. This evaluation uses a digital solute-transport model to estimate the future behavior of the brackish-water contamination based on alternative water-use scenarios.

The third section of this report describes the ground-water chemistry of the Patuxent and Patapsco aquifers. The chemical quality of ground water is an important consideration in the use and management of an aquifer system. This chemical quality results from the chemical interaction of recharge water with aquifer material. An understanding of these chemical processes makes it possible to estimate water quality for locations where data are scarce or unavailable.

ACKNOWLEDGMENTS

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University. The advice and help of Frederic R. Siegel, Roy C. Lindholm, and William Back of the George Washington University are gratefully acknowledged. The author wishes to thank the Baltimore City Department of Recreation and Parks for their full cooperation in the test well drilling program of this project. The cooperation of the Maryland Port Authority, Federal Yeast Corporation, Bethlehem Steel Corporation, FMC Corporation, and Chemetals Corporation is acknowledged. David Drummond of the Maryland Geological Survey aided in ground-water sampling. This report was typed by Eva Cockey and edited by Sheryl Protani.

LOCATION OF STUDY AREA

The location of the study area is shown in figure 1. This area is bounded by the Fall Line to the west and the Chesapeake Bay to the east. The Gunpowder River marks the northern extent and the Magothy River roughly corresponds to the southern extent of the study area. This area includes southeastern Baltimore County, eastern Baltimore City, and northern Anne Arundel County.

The study area lies entirely within the Atlantic Coastal Plain physiographic province. This province, which extends from Georgia to New York, is underlain by predominantly unconsolidated clastic sediments that thicken to the southeast. These sediments range from Holocene to Mesozoic in age.

METHODS OF INVESTIGATION

The first phase of this study was to define the hydrogeologic framework of the Lower Cretaceous aquifer system near Baltimore. Much of this information had to be gathered in the field. This fieldwork consisted of:

- (1) Establishing an observation-well network for the Patuxent and Patapsco aquifers. This network for the most part included wells used for industrial, municipal, and domestic water supply. Plate 1 and figures 30 and 31 (at the end of the report) show the locations of wells used in this network.
- (2) Drilling four test holes and obtaining geologists' logs, sample cuttings, and geophysical logs from each site. These four holes were then screened, cased, and developed into permanent observation wells.

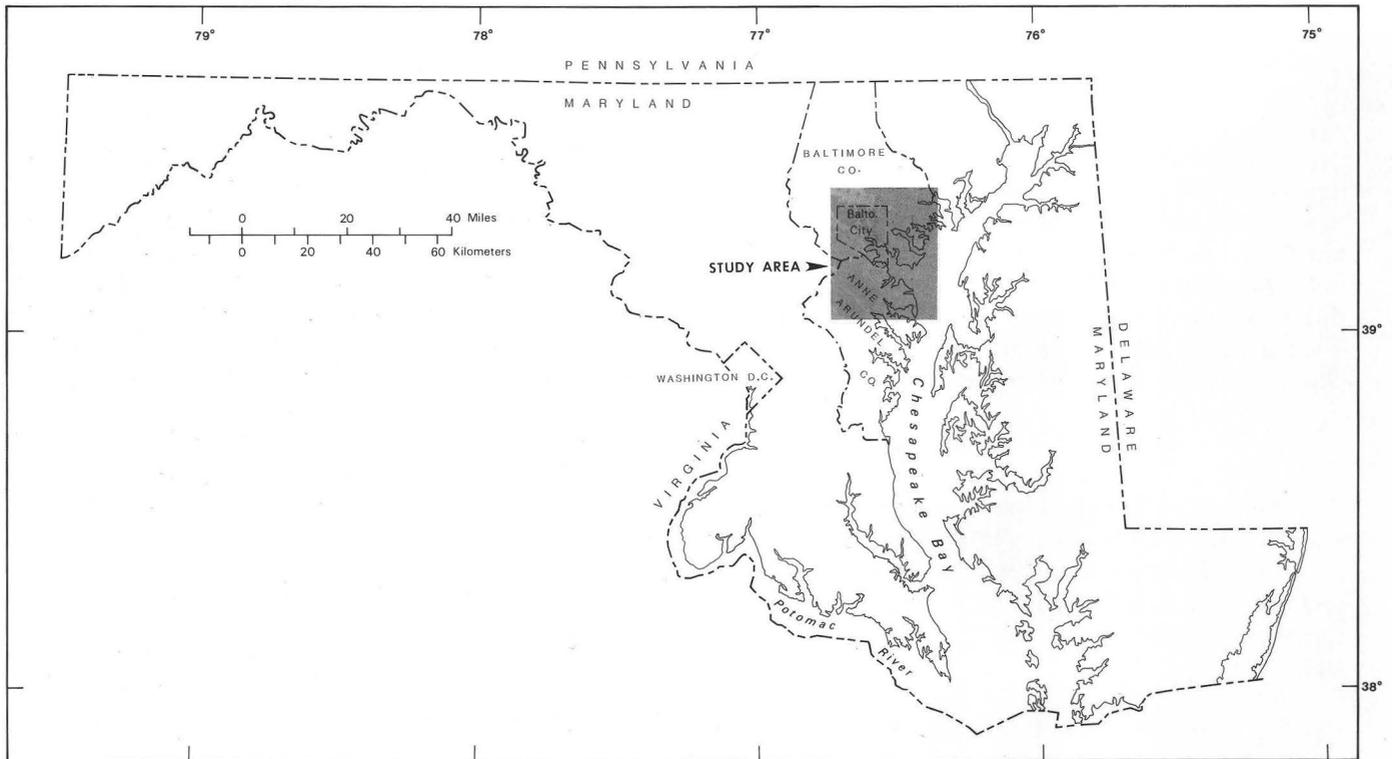


Figure 1.—Location of study area.

- (3) Obtaining pumpage information for major users of ground water. (See table 10 at the end of the report.)
- (4) Using the well network to obtain synoptic measurements of the Patuxent and Patapsco potentiometric surfaces.
- (5) Obtaining geophysical logs from existing wells.

In addition to fieldwork, a great deal of information was gathered from published and unpublished sources. This information included:

- (1) Drillers' logs of wells. (See table 11 at the end of the report.)
- (2) Information on historical water levels and historical pumpage.
- (3) Information on the transmissivity and storage properties of the aquifers.
- (4) Information on the stratigraphy, lithology, and sedimentary history of the Lower Cretaceous sediments.

The second phase of this project was to construct and calibrate a two-dimensional solute-transport model describing chloride contamination of the Patuxent aquifer. This effort included:

- (1) Developing a finite-difference grid for the

Baltimore area. This grid was designed so that it centered on the principal area of chloride contamination and coincided with appropriate boundaries.

- (2) Collecting information on aquifer transmissivity, thickness, porosity, areal extent, historical pumpage, and water levels. In addition, information on the thickness, areal extent, and hydraulic conductivity of the confining bed (Arundel Formation) that overlies the Patuxent aquifer was collected.
- (3) Translating the aquifer and confining-bed parameters onto computer data sets using the finite-difference grid.
- (4) Calibrating the ground-water flow portion of the model using historical water-level and pumpage data.
- (5) Calibrating the solute-transport portion of the model using data on the historical distribution of chloride contamination.
- (6) Using the calibrated model to estimate the future behavior of the chloride contamination plume based on alternative scenarios of aquifer use. These scenarios were designed to aid planners in making water-management decisions.

The third phase of the project was to describe the ground-water chemistry of the Patuxent and Patapsco aquifers. This investigation included:

- (1) Obtaining water samples from wells in the observation-well network. In order to obtain samples representative of aquifer water chemistry, only continuously pumping production wells were sampled. A total of 67 samples were collected and analyzed. The pH, alkalinity, temperature, conductivity, cold acidity, and concentrations of dissolved oxygen, hydrogen sulfide, and chloride were determined in the field according to standard U.S. Geological Survey sampling procedures. Samples were sent to the U.S. Geological Survey Central Laboratory in Atlanta, Ga., to determine concentrations of major and minor ions, trace and heavy metals, nutrients, and organic compounds.
- (2) Using the water-chemistry data, identify regions where water chemistry is controlled predominantly by:
 - (1) Naturally occurring water-mineral interactions.
 - (2) Brackish-water contamination.
 - (3) Urbanization-related contamination.
- (3) For the region controlled by natural chemical processes, graph major dissolved species as a function of distance along the flowpath. Based on this data, construct stoichiometric chemical models to explain observed water-chemistry changes.

- (4) For the region exhibiting urbanization-related contamination, show the distribution and concentrations of some organic compounds.

All thermodynamic data used in this report are taken from Plummer and others (1976).

PREVIOUS INVESTIGATIONS

The first comprehensive description of the water-bearing Coastal Plain formations near Baltimore was compiled by Darton (1896). Darton considered the Lower Cretaceous sediments as one geologic unit called the Potomac Formation. The Potomac Formation was later elevated to Group status and divided into the Patuxent, Arundel, and Patapsco Formations by Clark and Bibbins (1897). Clark, Mathews, and Berry (1918) provide a detailed description of water use in Baltimore during the late 19th and early 20th centuries. Geyer (1945) provides much data on pumpage during the early 20th century and consequent changes in water levels. Bennett and Meyer (1952) compiled a very detailed description of ground water in the Baltimore industrial area. This work includes inventories of pumpage, water quality, and aquifer characteristics. The study by Bennett and Meyer (1952) is notable in that it is one of the first applications of flow-net analysis to evaluate aquifer transmissivity. Ground-water use in the Baltimore industrial area was updated by Otton and others (1964). Glaser (1969) provides a detailed description of the petrology and sedimentary history of the Cretaceous sediments in Maryland. Hansen (1969) interprets the sedimentary environments associated with the Potomac Group based on electric log data.

GEOLOGY

REGIONAL GEOLOGIC AND STRATIGRAPHIC FRAMEWORK

The Lower Cretaceous sediments in the Baltimore area consist predominantly of unconsolidated clay, silt, sand and gravel beds. These beds crop out parallel to the Fall Line and dip to the southeast at about 80 ft/mi. The Coastal Plain sediments in the Baltimore area are underlain by Precambrian and(or) Paleozoic gneiss, schist, and gabbroic rocks that generally are referred to as "basement" rocks.

The surface of the basement rocks underlying the Baltimore area forms a structure termed the "Salisbury Embayment" (Richards, 1948). The Salisbury Embayment is part of a much larger basement structure called

the Chesapeake-Delaware Embayment (Murray, 1961). Hansen (1978) proposes that downwarping during Late Jurassic and Early Cretaceous time was accentuated in the Salisbury Embayment resulting in the presently observed structure. The Baltimore area occupies a north-central position on the Salisbury Embayment.

The generalized stratigraphy of the Baltimore area is shown in table 1. The Patuxent Formation (Barremian) nonconformably overlies the crystalline basement rocks. The Patuxent is overlain conformably by the Arundel Formation (Aptian). The Arundel is disconformably overlain by the Patapsco Formation (Albian) which, in turn, is overlain unconformably by deeply incised sediments of Pliocene and Pleistocene (?)

Table 1.—Generalized stratigraphy of the Baltimore area

System	Series	Stratigraphic unit	Stage ¹	Thickness (feet)	Dominant lithologic character	Water-bearing properties	
Quaternary and Tertiary	Holocene Pleistocene Pliocene(?)	Lowland and upland deposits	-	0-100	Sand, silty clay, and gravel; tan to rusty orange; predominantly quartz, illite and kaolinite.	Capable of yielding moderate quantities of water, but not commonly used as an aquifer in the Baltimore area. Subject to brackish-water encroachment in area adjacent to estuaries.	
Cretaceous	Lower Cretaceous	Potomac Group	Patapsco Formation ²	Albian	0-200	Sand, interbedded with lenses of silty clay; predominantly quartz, illite, and kaolinite.	Yields large quantities of water. Hydraulically connected with overlying Pleistocene sands. Subject to brackish-water encroachment in areas adjacent to estuaries.
			Arundel Formation	Aptian	25-200	Clay, interbedded with lenses of sandy silt; lignitic material common; predominantly illite and kaolinite.	Functions as a confining bed.
			Patuxent Formation	Barremian	50-250	Sand, gravel, interbedded with discontinuous lenses of clayey silt. Predominantly quartz. Iron-oxide cementation common in outcrop area.	Most important water-bearing formation in the Baltimore area. Yields large quantities of water, particularly in lower part of the formation. Subject to brackish-water contamination where overlying Arundel Formation has been removed by Pleistocene erosion.
Paleozoic and Precambrian		Crystalline Rocks (basement)	-	Unknown	Complex assemblage of schist, gneiss, and gabbro.	Yields small to moderate quantities of water west of the Fall Line. Not an important water-bearing formation in the Coastal Plain.	

¹ From Doyle, Van Campo, and Lugardon (1975).

² Designated Lower and Lowermost Upper Cretaceous by the U.S. Geological Survey.

age. In northeastern Maryland, the upper part of the Patapsco Formation is designated Lower and Lowermost Upper Cretaceous by the U.S. Geological Survey. In the Baltimore area, however, Patapsco sediments appear to be exclusively Lower Cretaceous. The subsurface relationships of Lower Cretaceous sediments near Baltimore are shown on plate 2.

PATUXENT FORMATION

Structure

The approximate outcrop area and altitude of the top of the Patuxent Formation is shown in figure 2. The Patuxent Formation dips to the southeast at about 80 ft/mi. A concave bend of the contours northeast of Baltimore is also evident from figure 2. This pattern reflects the basement-rock structure of the Salisbury Embayment.

Lithology and Mineralogy

The Patuxent Formation is composed primarily of quartzose gravel and sand interbedded with lenses of silty clay. An overall upward decrease in average grain

size is an important characteristic of Patuxent lithology. The basal portion consists of gravel and coarse sand with only minor amounts of silty clay. The upper portion of the formation, however, is predominantly fine sand and silty clay. Cycles of small-scale (5-20 ft thick) fining-upward sequences occur throughout the Patuxent Formation. Cuttings from well 3S5E-46 are described in table 2. These cuttings include a representative section of the Patuxent Formation and illustrate the diverse lithology.

Gamma logs are a useful tool for evaluating the lithology of drilled boreholes and wells. They are particularly useful when drill cuttings of formational material are available for comparison with the log (Selley, 1978, p. 22). A gamma log records the natural gamma radiation in a rock unit. Because clay and silt usually have a higher proportion of radioactive materials than quartzose sand or gravel, they give higher "kicks" on a gamma log. A gamma log records, therefore, the relative percentage of silt and clay to quartz sand and gravel present in the formation.

The overall trend toward decreasing grain size in the upper sections of the Patuxent are illustrated by the gamma logs shown on plate 2. Furthermore, a conspicuous small-scale fining-upward sequence is clearly observable between about 300 and 320 ft on the gamma log of well 3S5E-46.

Table 2.—Lithologic description of cuttings from well 3S5E-46 (Location shown on plate 1)

Environments of Deposition

Geologic unit	Lithology	Interval thickness (feet)	Depth to top of interval (feet)
Pleistocene sediments	Silt, clayey with fine sand and gravel, tan to light gray; quartz and kaolinite are most abundant minerals; small chunks of iron-cemented sandstone observed.	10	0
Patapsco Formation	Sand, silty, orange-tan to gray; sand grains are angular to subangular; quartz is most abundant mineral (90-98 percent); lignite, metamorphic rock fragments, plagioclase, kaolinite, muscovite, and iron oxide fragments present in minor and trace amounts.	40	10
	Sand, silty, gravelly, yellowish-tan; sand grains angular to subangular; gravel cobbles are subrounded; quartz is most abundant mineral (90-98 percent); lignite, metamorphic rock fragments, plagioclase, orthoclase, kaolinite, muscovite, and chunks of iron oxide-cemented sandstone present in trace amounts.	20	50
Arundel Formation	Clay, silty, reddish-brown; kaolinitic with traces of lignite and pyrite.	10	70
	Clay, reddish-brown with streaks of yellow; kaolinitic with traces of lignite and pyrite.	120	80
Patuxent Formation	Silt, sandy, clayey, reddish-brown; quartz and kaolinite are most abundant minerals (95-99 percent); traces of lignite, metamorphic rock fragments, and plagioclase.	30	200
	Sand, silty, reddish-brown; quartz and kaolinite are most abundant minerals (95-99 percent); traces of iron oxide, plagioclase, muscovite, and lignite present.	20	230
	Sand, gravelly, silty, reddish-brown; quartz is most abundant mineral (95-98 percent); minor and trace amounts of plagioclase, lignite, iron oxides, and orthoclase are present.	150	250

The Patuxent Formation in the Baltimore area is entirely continental in origin (Glaser, 1969, p. 71). Features such as marine fossils or authigenic marine minerals have never been observed in this area. The Patuxent Formation records fluvial sedimentation that occurred primarily in a braided-stream environment (Glaser, 1969, p. 72; Hansen, 1969, p. 1933). The overall fining-upward trend of Patuxent sediments suggests that in late Patuxent time the river system grew progressively more meandering in character. The gravel sequences in the Patuxent probably record in-channel sedimentation of braided streams. Sand beds inter-layered with the gravel generally exhibit trough cross-bedding. These sands most likely represent subaqueous sand waves and dunes. In outcrop, lenses of silty clay preserved between coarser beds are frequently observed to pinch out laterally. These clay lenses, particularly in the coarser part of the section, probably record channel cutoffs that were subsequently infilled with fine-grained material.

The upper third of the Patuxent Formation consists predominantly of fine sand and silt. This change in lithology is interpreted as recording a lowering of stream gradients that changed the streams from predominantly braided to predominantly meandering in character. According to this interpretation, the multi-colored silty clays in the upper part of the Patuxent probably record overbank or levee sedimentation.

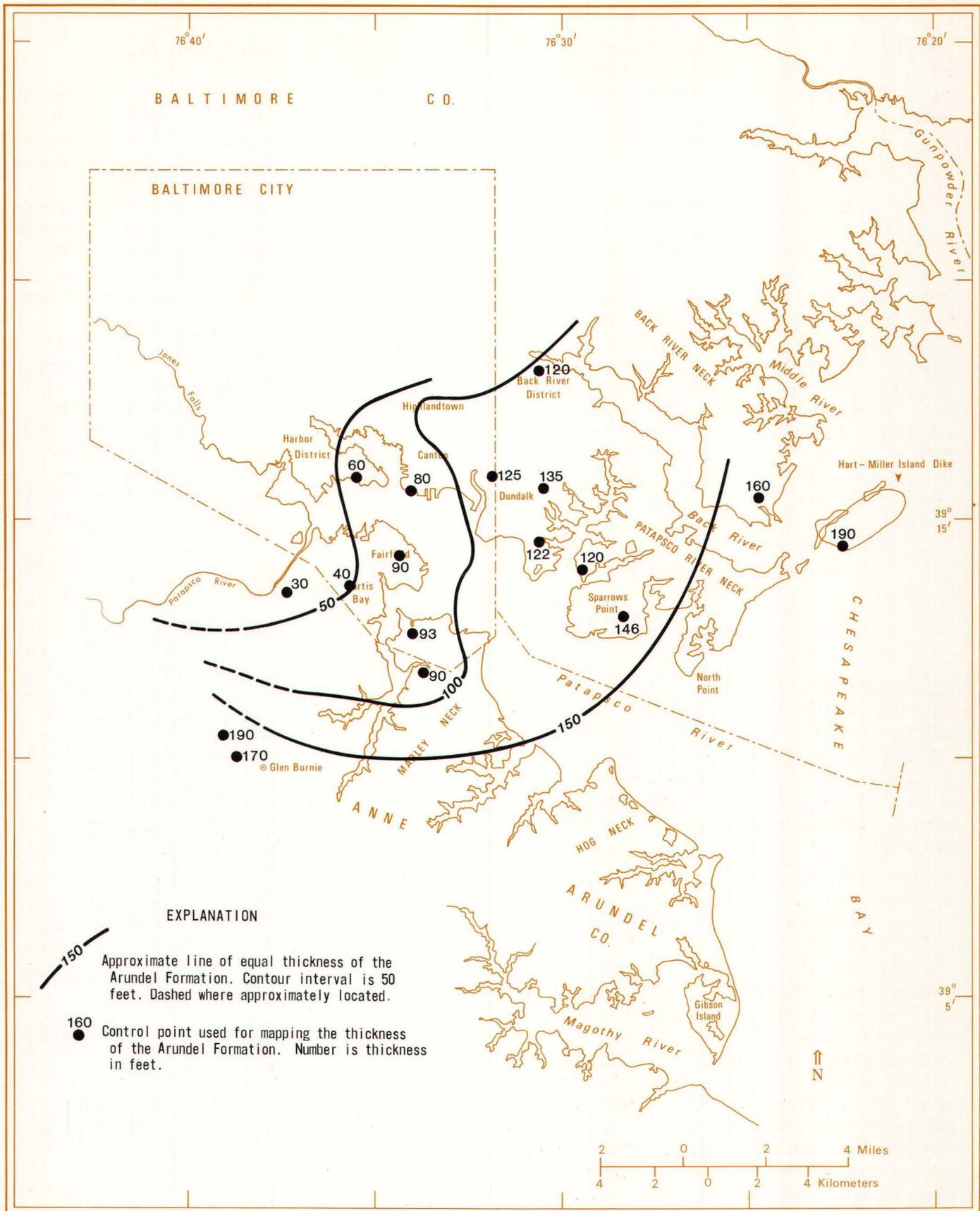
Patuxent gravel is typically composed of subrounded quartz pebbles ranging from about 1/6 to 3/5 in. in diameter. In outcrop, this gravel commonly is cemented by iron oxyhydroxides, but is usually un lithified in the subsurface. Patuxent sand is overwhelmingly quartz with small amounts of feldspar and heavy minerals. Material other than quartz makes up less than 1 percent of the sand fraction. The feldspar consists of a mixture of pink orthoclase and white plagioclase. Sand grains in the Patuxent generally are angular to subangular. Silt-clay beds in the Patuxent are laterally discontinuous and form lenticular beds. They are commonly pale-gray to light brown in the lower part of the section. The upper part of the section is characterized by pale and red-yellow multicolored clays and silts. X-ray analyses of this fine-grained material indicate that it consists entirely of illite and kaolinite in varying proportions (Knechtel and others, 1961). Smectites, chlorite or other clay minerals have never been reported. Fragments of lignitized wood, usually associated with secondary pyrite, are common in the Patuxent Formation. The heavy mineral suite that has been reported (Glaser, 1969, p. 54) includes staurolite, zircon, kyanite, tourmaline, rutile, and almandine garnet.

ARUNDEL FORMATION

Lithology and Mineralogy

The Arundel Formation in the Baltimore area consists predominantly of a dense, plastic clay with thin lenses of silt. The Arundel usually is red to red-yellow in color. Some localities of the Arundel are characterized by an abundance of ferruginous nodules. These nodules usually are composed of siderite or pyrite (Knechtel and others, 1961, p. 8). Pyrite nodules frequently are observed to retain the imprints of twigs or other wood fragments. The distribution of lignite in the Arundel is variable. Some localities exhibit abundant lignite and others, very little. Kaolinite and illite with minor amounts of mixed-layer clays are the dominant clay minerals in the Arundel. The fossilized remains of dinosaurs have been reported from some localities of the Arundel Formation (Glaser, 1969, p. 18).

A lithologic description of cuttings from well 3S5E-46 is shown in table 2. This table includes a representative section of the Arundel Formation. The gamma log traces shown on plate 2 indicate the relative clayey character of the Arundel as compared to the Patuxent Formation.



Base map from the Maryland Geological Survey County Topographic Map Series, 1:62,500

Figure 3.—Thickness of the Arundel Formation.

The approximate thickness of the Arundel Formation is shown in figure 3. Although a consistent thickening trend to the southeast is evident, thicknesses at individual locations are quite variable. It is possible that this is due to post-depositional erosion during the Arundel-Patapsco hiatus.

Environments of Deposition

The clay- and silt-sized material that makes up the Arundel Formation indicates deposition in a low-energy flow regime. As with the Patuxent Formation, there is no evidence of marine sedimentation in the Arundel. The evidence of dinosaur fossils combined with the presence of lignitized plant material suggests that Arundel sedimentation occurred in a marshy environment. Clastic sedimentation was sufficient, however, to preclude the development of peat beds. Stream gradients in this environment must have been very low. This resulted in very sluggish streams that meandered on a broad flood plain.

PATAPSCO FORMATION

Structure

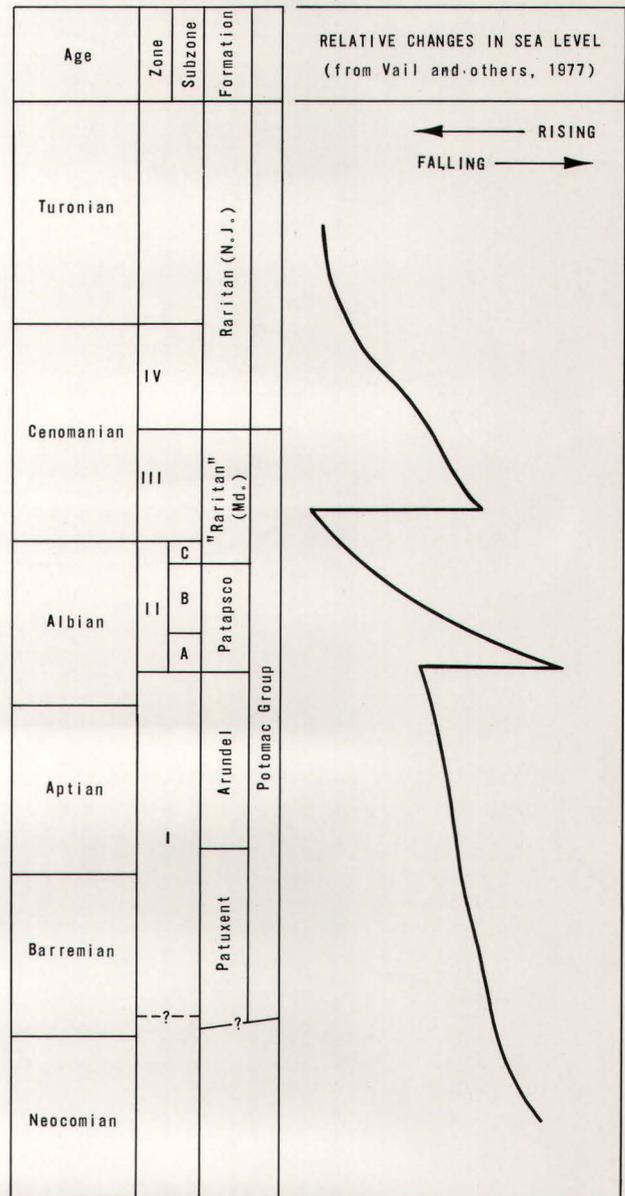
The Patapsco Formation crops out or underlies sediments of Pliocene and Pleistocene age in the Baltimore area. This relationship is illustrated on plate 2. Plate 2 also shows that the Patapsco Formation dips southeast at about 80 ft/mi. This pattern, which is identical to the Patuxent Formation, reflects the continued influence of basement-rock structure on sedimentation during Albian time.

Lithology and Mineralogy

The Patapsco Formation in the Baltimore area consists of interbedded sands, silts, and clays. Silt- and clay-sized material typically makes up 40 to 60 percent of the total section. The sand-sized material is predominantly quartz with trace amounts (less than 1 percent of the total) of feldspar and heavy minerals. The heavy mineral suite of the Patapsco includes zircon, staurolite, kyanite, rutile and tourmaline. Discontinuous ledges of iron hydroxide-cemented sandstones and conglomerates are reported from some localities. The clay mineral suite of the Patapsco consists entirely of kaolinite and illite. Pyrite mineralization associated with lignitic material is common. The resistivity log of well BA-Gg 13 (pl. 2) shows a representative section of the Patapsco Formation.

Environments of Deposition

The Patapsco Formation in the Baltimore area was deposited entirely under continental conditions (Glaser, 1969, p. 72). No evidence of marine fossils or authigenic marine minerals have been reported in the Baltimore area. In outcrop, individual fining-upward sequences 5 to 20 ft thick are common. These units typically contain 50 to 70 percent silt- or clay-sized material. The abundance of fine-grained material in individual fining-upward sequences and, in the section as a whole, suggests that a meandering-stream environment dominated much of Patapsco sedimentation.



(from Doyle, Van Campo, and Lugardon, 1975)

Figure 4.—Comparison of Lower Cretaceous geologic units with eustatic sea-level changes.

EUSTATIC SEA-LEVEL CHANGES DURING LOWER CRETACEOUS TIME

The lithology of the Potomac Group sediments near Baltimore suggests that stream gradients underwent significant changes during Early Cretaceous time. The basal Patuxent Formation represents a high-gradient, braided-river environment. The upper part of the Patuxent appears to represent a moderate-gradient meandering-stream environment. The upper part of the Patuxent then conformably grades into the Arundel Formation, which records a low-gradient marshy environment. Finally, the Patapsco Formation was deposited in a moderate-gradient meandering-stream environment.

Hansen (1969, p. 1935) has discussed three possible causes for the observed changes in stream gradients: (1) A paleoclimatic change affecting stream discharge, (2) capture and diversion of the axial river, and (3) a eustatic change in sea level.

There is some evidence that the observed stream-gradient changes resulted from eustatic sea-level changes. Vail and others (1977, p. 85) have published a set of graphs that record relative changes in global sea levels as a function of time. These graphs were inferred from drilling and seismic data obtained from continen-

tal margins throughout the world. These curves record geotectonic, glacial, or other large-scale phenomenon and exclude effects of local progradations. A comparison of Vail's global cycles with the stratigraphic ages of Potomac Group sediments (Doyle and others, 1975) is shown in figure 4. The comparisons shown in figure 4 suggest that Patuxent sedimentation was initiated during a relatively low stand of sea level. Initial Patuxent sedimentation would have occurred, therefore, in a high-energy environment. The subsequent sea-level rise during Barremian time would have then lowered stream gradients, gradually culminating in the low-energy sedimentation of Aptian time. The beginning of Albian time reflects a sharp decrease in sea level. This corresponds to an increase in stream gradients recorded by coarser Patapsco sediments.

Although Vail's sea-level curves apparently correlate with stream-gradient changes recorded in sediments of the Potomac Group, this should be viewed with some reservation. The absolute ages of Potomac sediments are uncertain. Similarly, Vail's sea-level curves have not been independently verified. Thus, the correlation between stream gradients recorded in Potomac Group sediments and eustatic sea-level changes should be considered a working hypothesis rather than an established fact.

HYDROGEOLOGY

PATUXENT AQUIFER

Regional Extent

The Patuxent Formation is used extensively as a source of fresh water in Baltimore County, Baltimore City, and Anne Arundel County in Maryland. To a lesser degree, the Patuxent Formation is a source of water in northeastern Maryland and southern Maryland. Records of selected wells screened in the Patuxent aquifer are included in table 9 (at the end of the report).

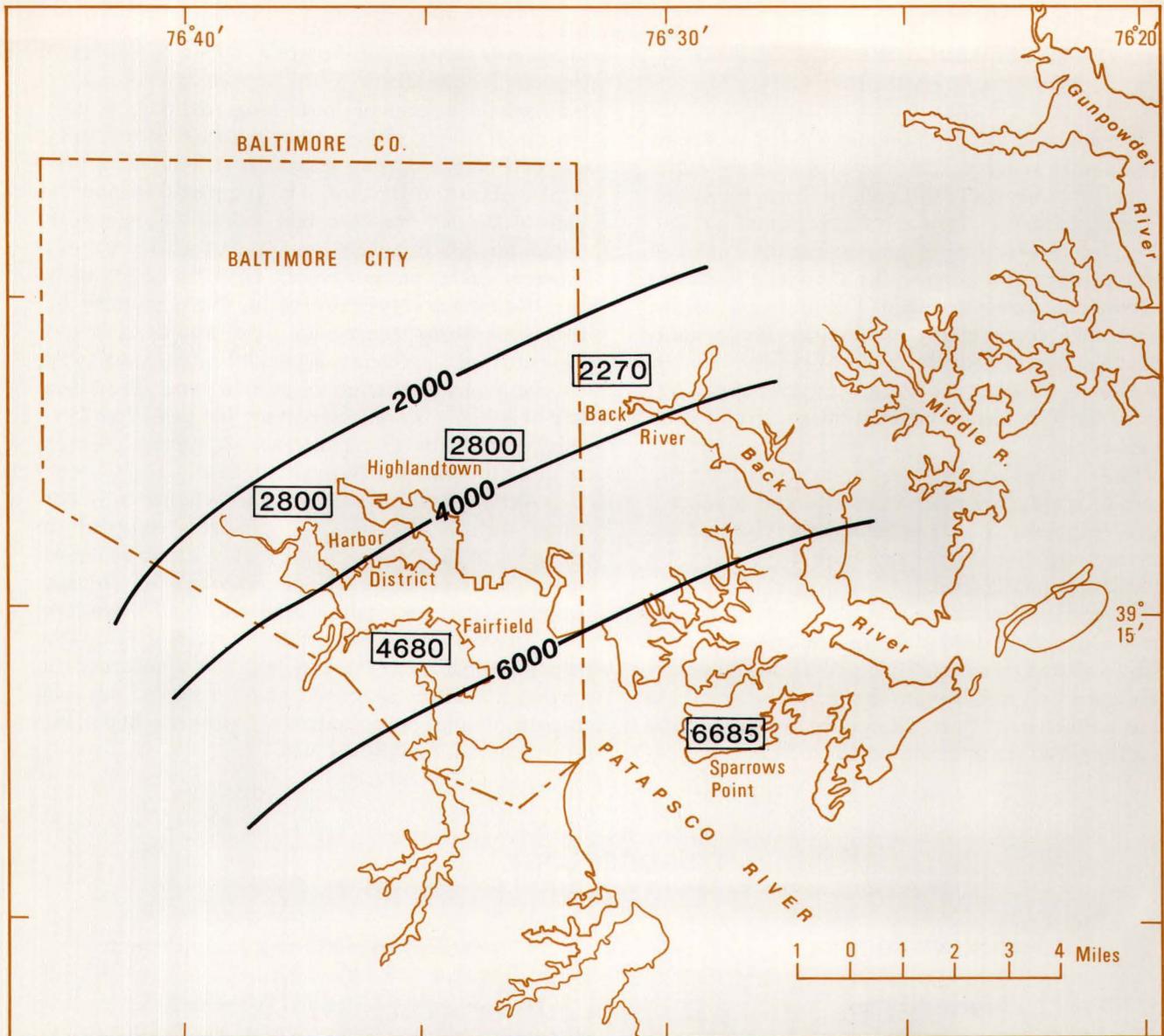
The Patuxent Formation in Maryland is most productive as a water source in the braided-stream facies identified by Hansen (1969, p. 1934). This facies consists primarily of coarse, well-sorted sands and gravels that have high permeability. Baltimore County, Baltimore City and northern Anne Arundel County lie entirely within the braided-stream facies of the Patuxent Formation. The upper and lower flood-plain facies identified by Hansen (1969, p. 134) are present exclusively in northeastern Maryland and southern Maryland. For the purposes of this report, the term "Patuxent aquifer" refers exclusively to the braided-stream facies of the Patuxent Formation.

Transmissivity and Storage Coefficient

Transmissivity is defined as the rate that water is transmitted through a unit width of aquifer under a unit hydraulic gradient (Lohman and others, 1972, p. 6) and is related to aquifer thickness and hydraulic conductivity. However, local lithologic inhomogeneities make a direct correlation between aquifer thickness and transmissivity unfeasible. In practice, therefore, the transmissivity is usually determined by analyzing pumping-test data or other hydrologic information.

The approximate transmissivity distribution of the Patuxent aquifer near Baltimore was evaluated by Bennett and Meyer (1952, p. 47-58), who used pumping-test data supplemented by a classic example of flow-net analysis. In general, the transmissivity values obtained from pumping-test data were slightly lower than values obtained from the flow-net analysis. However, because the flow-net analysis is less dependent on localized inhomogeneities, the values are probably more representative in a regional context than pumping-test values.

The transmissivity distribution of the Patuxent aquifer in the Baltimore area as modified from Bennett and Meyer (1952, p. 56) is shown in figure 5. There is a



EXPLANATION

6685 Transmissivity as determined by flow-net analysis (Bennett and Meyer, 1952, p. 56) Number is calculated transmissivity in feet squared per day.

—2000— Approximate line of equal transmissivity. Interval is 2000 feet squared per day.

Figure 5.—Transmissivity of the Patuxent aquifer.

general trend of transmissivity increase to the southeast that coincides with increasing thickness of the formation in that direction.

The storage coefficient of an aquifer is defined as the volume of water released from a unit surface area of

aquifer per unit drop in head (Lohman and others, 1972) and is a dimensionless quantity. In confined aquifers, water derived from storage comes in part from expansion of water and compression of aquifer material. A commonly used method for determining storage

coefficient values is by analysis of pumping-test data using the Theis equation (Lohman and others, 1972). Reported values of storage coefficient in the confined portion of the Patuxent aquifer (Bennett and Meyer, 1952, p. 51) range from 0.00019 to 0.000038.

Upper and Lower Confining Beds

There is little information available on the hydraulic properties of the crystalline basement rocks that underlie the Patuxent aquifer. Where these rocks crop out, however, they have very little primary permeability. Water in these rocks is found in secondary fractures and cracks. This permeability is generally several orders of magnitude less than that of the Patuxent aquifer. For the purposes of this report, the basement rocks will be considered impermeable. Basement rocks in the Baltimore area act as the lower confining bed to the Patuxent aquifer.

The Arundel Formation acts as the upper confining bed of the Patuxent aquifer. The Arundel Formation is an extremely dense, tight clay that exhibits very low vertical hydraulic conductivities. Estimates of Arundel Formation vertical hydraulic conductivities range from 10^{-9} to 10^{-11} ft/s (Mack and Achmad, oral comm., 1983).

Historical Pumpage and Water Levels

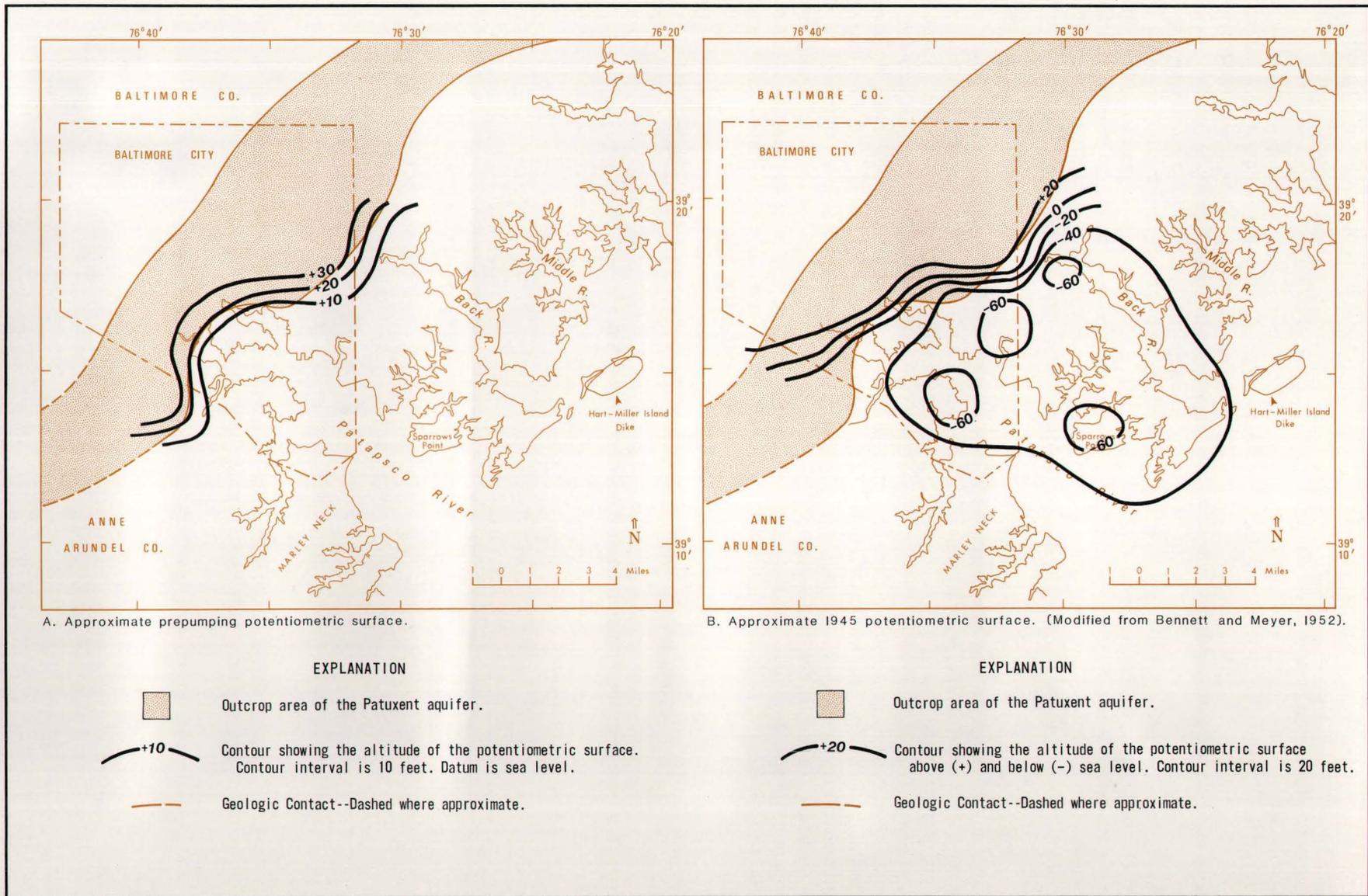
The Patuxent aquifer was first used as a water source in the Baltimore area about 1850. Water use increased during the late 19th century and by 1900, pumpage totaled about 7 Mgal/d. Pumpage continued to increase after the turn of the century and by 1945, about 28 Mgal/d were being pumped. After 1945, pumpage gradually decreased and in 1982, pumpage totaled approximately 11 Mgal/d. The pumpage history of the Patuxent aquifer is summarized in table 3. Ground-water appropriations for present large users of the Patuxent aquifer are listed in table 10.

It is difficult to estimate the prepumping potentiometric surface of an aquifer. This difficulty is due primarily to a lack of recorded water levels early in the development of an aquifer. In the Baltimore area, however, Darton (1896, p. 137-141) has tabulated the records of wells, including water levels, of about 90 wells drilled from 1850 through 1890. This data, combined with additional water levels tabulated by Clark and others (1918, p. 355-364), permits an approximate reconstruction of the Patuxent aquifer prepumping potentiometric surface. This approximate reconstruction is shown in figure 6a.

Table 3.—Pumpage history of the Patuxent aquifer near Baltimore, Md.

Years	Digital model pumping period	Principal sources of pumpage data	Pumpage (million gallons per day)																				
			Curtis Bay District				Fairfield District				Harbor District	Highland-town District	Canton District	Back River District	Dundalk District	Sparrows Point District	Glen Burne District						
			05-08	06-07	07-11	08-09	08-13	09-08	09-09	10-07	09-05	10-05	13-04	13-05	12-06	16-06	17-06	13-07	13-08	13-09	14-13	15-13	15-14
851-1860	1	(1)	-	-	-	-	-	-	-	0.25	0.25	-	-	0.5	-	-	-	-	-	-	-	-	-
861-1870	2	(1)	-	-	-	-	-	-	-	.5	.5	-	-	1.0	-	-	-	-	-	-	-	-	-
871-1880	3	(1)	-	-	-	-	-	-	-	.75	.75	-	-	1.5	-	-	-	-	-	-	-	-	-
881-1890	4	(1)	-	-	-	-	-	-	-	1.0	1.0	-	-	2.0	-	-	-	-	-	-	-	-	-
891-1900	5	(1)	-	-	-	-	-	0.25	0.25	-	1.25	1.25	-	-	2.5	-	-	-	0.25	0.25	-	-	-
901-1910	6	(1)	-	-	-	-	.3	.3	-	1.25	1.25	0.25	0.25	2.0	-	-	-	0.5	0.5	-	-	-	-
911-1920	7	(1)	-	-	2.0	-	.5	.5	-	1.0	1.0	0.5	0.5	1.5	0.5	-	-	1.5	1.5	1.0	1.0	1.0	-
921-1930	8	(1)	-	-	3.0	-	1.0	1.0	-	1.0	1.0	1.0	1.0	1.0	1.0	-	-	1.75	1.75	1.7	1.7	1.7	-
931-1935	9	(1)	-	-	6.3	-	1.5	1.5	-	1.05	1.05	1.25	1.25	0.5	1.5	-	-	2.0	2.0	3.3	3.3	3.3	-
936-1941	10	(1)	-	-	3.3	-	2.6	2.6	-	1.05	1.05	1.4	1.4	0.5	2.0	-	-	2.05	2.05	5.8	5.8	5.8	-
942-1945	11	(1)	-	-	3.3	-	2.6	2.6	-	1.05	1.05	1.4	1.4	0.5	2.0	-	-	2.5	2.5	2.5	2.5	2.5	-
946-1950	12	(2)	-	-	3.3	-	1.3	1.3	-	.5	.5	1.0	1.0	0.2	1.5	-	-	2.4	2.4	2.7	2.7	2.7	-
951-1955	13	(2)	-	-	3.3	-	1.3	1.2	-	.12	.12	0.6	0.6	0.1	1.1	-	-	2.4	2.4	2.7	2.7	2.7	-
956-1960	14	(3)	0.003	-	0.04	0	-	-	1.8	-	-	-	-	-	-	1.1	.65	0.5	0.5	2.0	2.0	2.0	2.0
961-1965	15	(3)	.006	0.003	.04	0	0.2	-	1.9	-	-	-	-	-	-	1.1	1.0	-	-	1.8	1.8	1.8	2.0
966-1970	16	(3)	.007	.006	.04	0	0.4	-	2.0	-	-	-	-	-	-	1.1	1.3	-	-	1.7	1.7	1.7	2.0
971-1975	17	(3)	.008	.008	.02	0	.01	-	1.6	-	-	-	-	-	-	1.0	1.6	-	-	2.2	2.2	2.2	2.0
976-1980	18	(3)	.003	.006	.006	0	.01	-	0.5	-	-	-	-	-	-	0.8	2.4	-	-	1.8	1.8	1.8	2.0
981-1982	19	(3)	.001	.003	0	0	.01	-	0	-	-	-	-	-	-	0.8	2.5	-	-	1.63	1.63	1.63	2.0

¹ Bennett and Meyer (1952); Clark, Mathews, and Berry (1918); Darton (1896).
² Otton, Martin, and Durum (1964).
³ Maryland Water-Resources Administration Ground-Water Appropriation Permit Records.



Base map from Bennett, R.R. and Meyer, R.R., 1952

Figure 6.—Approximate prepumping and 1945 potentiometric surfaces of the Patuxent aquifer.

Bennett and Meyer (1952, pl. 13) published a map of the 1945 potentiometric surface of the Patuxent aquifer near Baltimore. This map is shown in modified form in figure 6b. Cones of depression in the Canton, Dundalk, Back River, and Sparrows Point districts are shown on the figure. The 1945 potentiometric surface was measured at the time when pumpage was at its highest historical level (table 3).

The potentiometric surface of the Patuxent aquifer was measured in May 1982 as part of this project. This map, which is shown in figure 7, shows that there has been a rise in water levels from 1945 through 1982. This water-level rise has occurred due to a decrease in pumpage since 1945 (table 3).

The locations and U.S. Geological Survey well numbers of observation wells and pumping wells for which data were collected in this study are shown on plate 1. Two wells in the Patuxent aquifer were drilled and completed as part of this study. The records of these wells are listed in table 4.

Chloride Contamination

In the 1930's, some users of Patuxent water began to experience problems with chloride contamination of their wells. It was observed that pumping wells nearest to the Patapsco River had the most contamination, whereas locations removed from the river had little or no contamination. The areal distribution of chloride contamination in 1945 was determined by Bennett and Meyer (1952). This distribution is reproduced in modified form in figure 8a. Based on this data, Bennett and

Meyer concluded that the contamination originated where the Patuxent Formation subcropped beneath the Patapsco River.

Chloride contamination has continued to be a major water-quality problem since first identified by Bennett and Meyer. The approximate distribution of chloride contamination in 1982 is shown in figure 8b. A comparison of figure 8a with figure 8b shows that since 1945, the contamination plume has shifted to the southeast by about 1.5 mi. A quantitative approach to the movement of chloride contamination is presented in the next section of this report.

PATAPSCO AQUIFER

Regional Extent

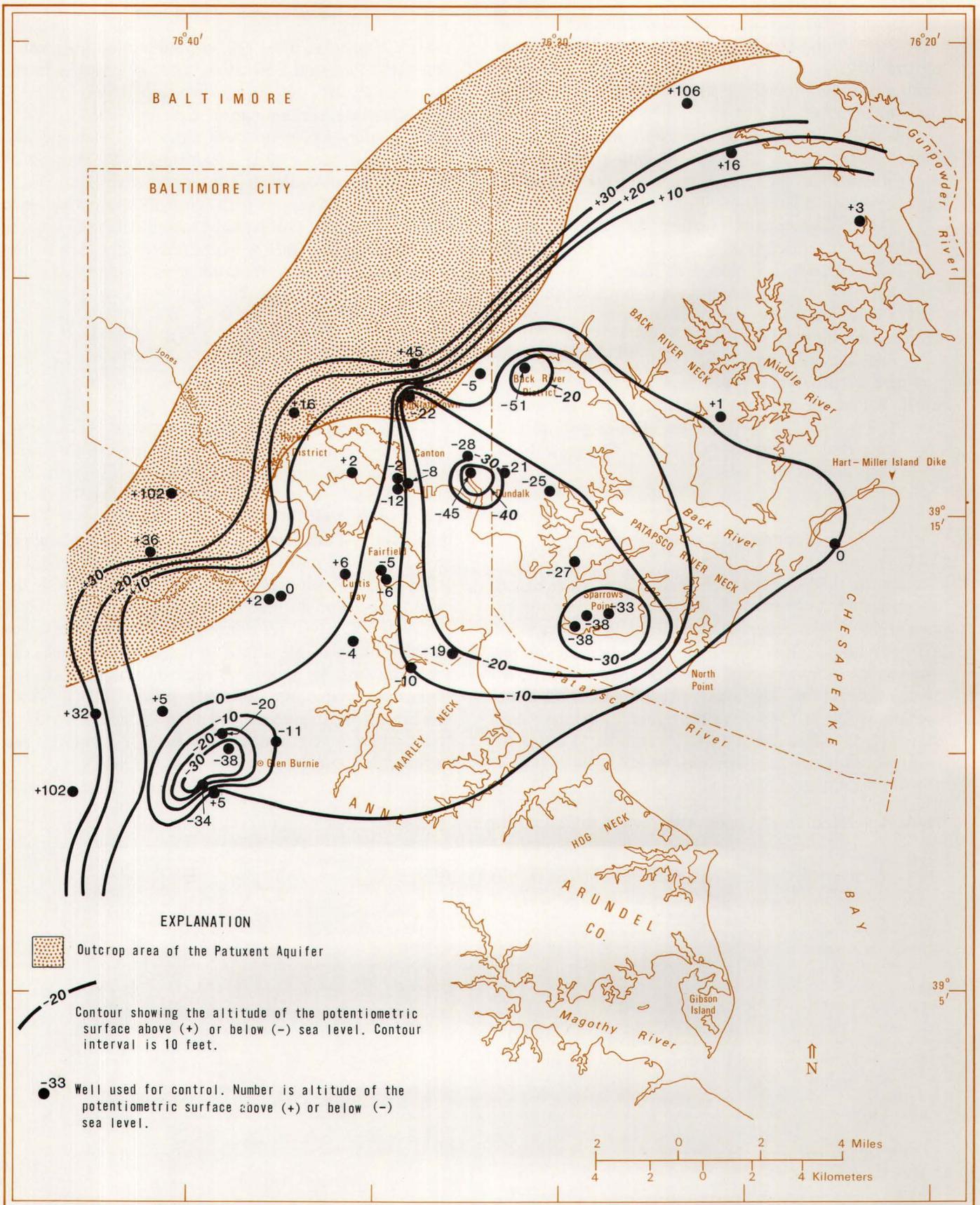
The Patapsco Formation is used as a source of fresh water in Baltimore County, Baltimore City, and Anne Arundel County in Maryland. It has been divided into a "sand" facies and a "clay" facies by Reinhardt and Crowley (1979). The sand facies consists predominantly of medium to fine sand and has moderate (1 to 0.1 ft/d) permeabilities. In the Baltimore area, the Patapsco Formation coincides predominantly with the sand facies. For the purposes of this report, the term "Patapsco aquifer" refers exclusively to the sand facies of the Patapsco Formation. In the Baltimore area, the Patapsco aquifer coincides almost exactly with the Patapsco Formation. In other parts of Maryland, however, this coincidence may not hold true. Records of selected wells screened in the Patapsco aquifer are included in table 9.

Table 4.—Records of observation wells drilled during the project

USGS Well No.	State permit No.	Latitude Longitude	Altitude of land surface (feet)	Date drilled	Drilled depth (ft below land surface)	Construction data		Geophysical logs 1/	Driller	Static water level (feet below land surface measured on 7/06/83)	Aquifer	Locality
						Casing diameter (inches)	Screen position (feet below land surface)					
3S5E-46	BC 81-0088	39°15'56" 76°31'55"	10	10/20/82	409	4	40- 50	GG, N, M, S, G, C	East Coast Well and Pump Co.	0	Patapsco	Colgate Creek
3S2E-5	BC 81-0087	39°16'00" 76°35'33"	15	10/26/82	185	4	137-147	GG, N, M, S, G, C	East Coast Well and Pump Co.	17	Patuxent	Latrobe Park
5S2E-24	BC 81-0089	39°13'47" 76°35'47"	75	10/29/82	359	4	260-270	G	East Coast Well and Pump Co.	64	Patuxent	Farring Park
5S2E-25	BC 81-0090	39°13'47" 76°35'47"	75	11/02/82	120	4	105-115	G	East Coast Well and Pump Co.	46	Patapsco	Farring Park

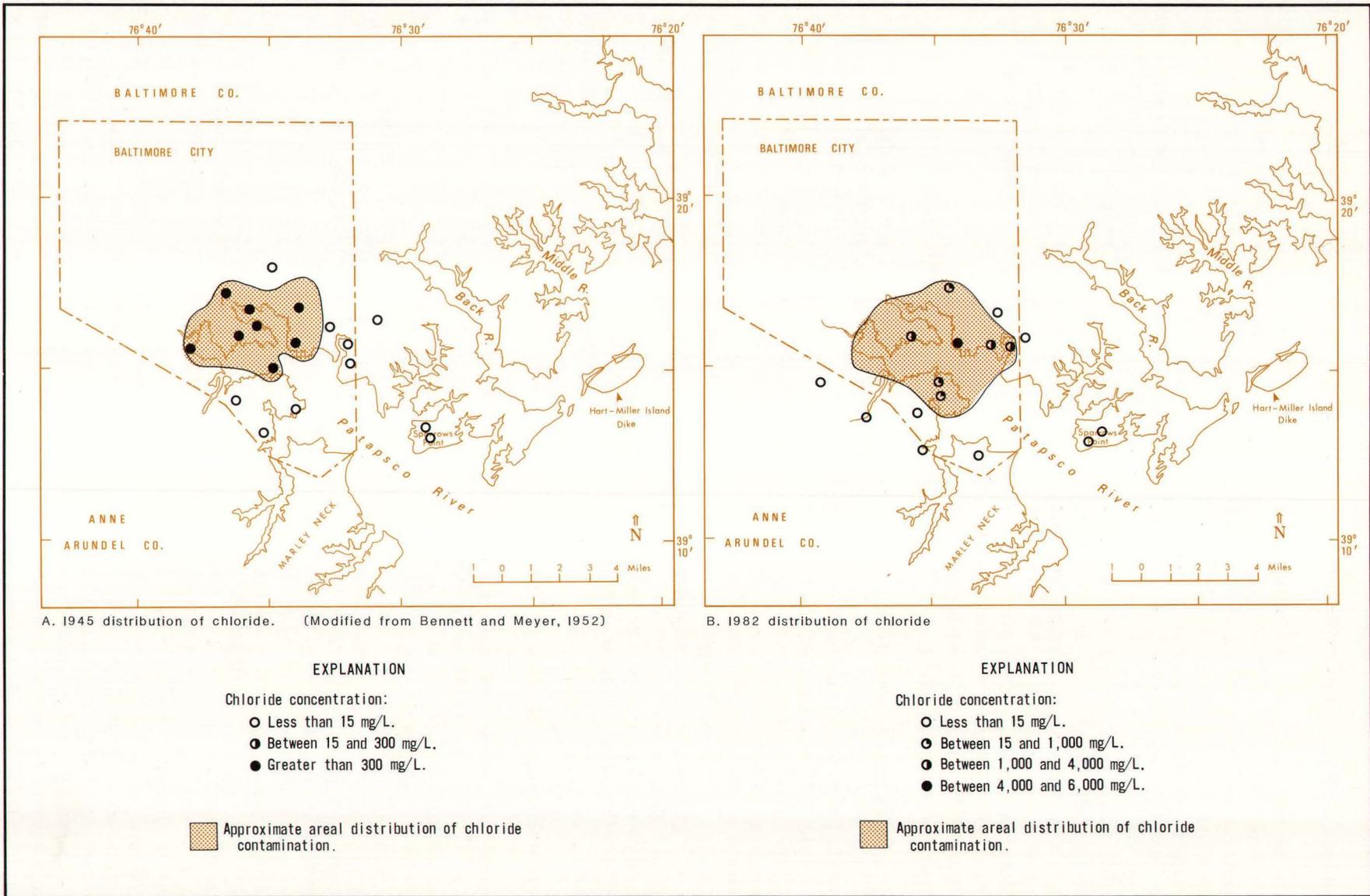
1/ Type of geophysical logs:

GG = Gamma-gamma density
 N = Neutron
 M = Multipoint electric
 S = Single-point electric
 G = Natural gamma
 C = Caliper



Base map from the Maryland Geological Survey County Topographic Map Series, 1:62,500

Figure 7.—Potentiometric surface of the Patuxent aquifer in 1982.



Base map from Bennett, R.R. and Meyer, R.R., 1952

Figure 8.— Areal distribution of chloride contamination of the Patuxent aquifer in 1945 and 1982.

Transmissivity and Storage Coefficient

Much of the Patapsco aquifer in the Baltimore area is unconfined. Where unconfined, the transmissivity depends on both the saturated thickness and aquifer permeability. In the Sparrows Point district, where the Patapsco is confined, reported transmissivity values range from 3,800 to 1,900 ft²/d (Bennett and Meyer, 1952, p. 67).

Only a few storage coefficients have been determined for the Patapsco aquifer in the Baltimore area. For the confined portion of the Patapsco, reported values range from 0.0027 to 0.000053, with an average of 0.00061 (Bennett and Meyer, 1952, p. 67). No storage coefficients have been reported for the unconfined portion of the Patapsco. It is estimated, however, that these values are on the order of 0.01 to 0.1.

Upper and Lower Confining Beds

The Arundel Formation acts as the lower confining bed of the Patapsco Formation. The water-bearing properties of the Arundel Formation have been discussed previously. Over much of the project area, the Patapsco outcrops or subcrops and does not have an upper confining bed. Where the Patapsco is confined above, however, fine-grained Pleistocene sediments act as the confining bed (table 1). The vertical hydraulic conductivity of these sediments have been reported as 10⁻⁷ to 10⁻¹⁰ ft/s (Mack and Achmad, oral comm., 1983).

Historical Pumpage and Water Levels

The Patapsco aquifer was the first hydrologic unit exploited as a source of water in Baltimore because of its relative accessibility. By 1900, about 3 or 4 Mgal/d was being produced, mainly in the Harbor and Canton districts of Baltimore City. Because the Patapsco aquifer subcrops extensively under the brackish Patapsco River, chloride contamination became a major problem in the early 20th century. Because of the chloride contamination problem, almost all pumpage from the Patapsco had ceased in the Harbor, Canton, and Dundalk districts by 1945. At this time, the only major user of the Patapsco aquifer was the Bethlehem Steel Plant at Sparrows Point. In 1945, pumpage from the Patapsco totaled about 3 Mgal/d. In the late 1940's and 1950's, however, many Patapsco wells in Sparrows Point became contaminated by chlorides and were eventually abandoned. At the present time there is no major use of the Patapsco aquifer in the immediate vicinity of the Patapsco River estuary. However, there is significant pumpage from the Patapsco occurring in northern Anne Arundel County. Ground-water appropriations

for present large users of the Patapsco aquifer are listed in table 10 (at the end of the report).

The first potentiometric map of the Patapsco aquifer was prepared by Bennett and Meyer (1952, pl. 14). This map, which is shown in figure 9a, shows that the only major cone of depression in 1945 was located in the Sparrows Point district. The approximate 1982 potentiometric surface of the Patapsco aquifer is shown in figure 9b. The data in figure 9b show that water levels have recovered significantly from 1945 levels in the Sparrows Point area.

The locations and U.S. Geological Survey well numbers of observation wells and pumping wells for which data were collected in this study are shown on plate 1.

Chloride Contamination

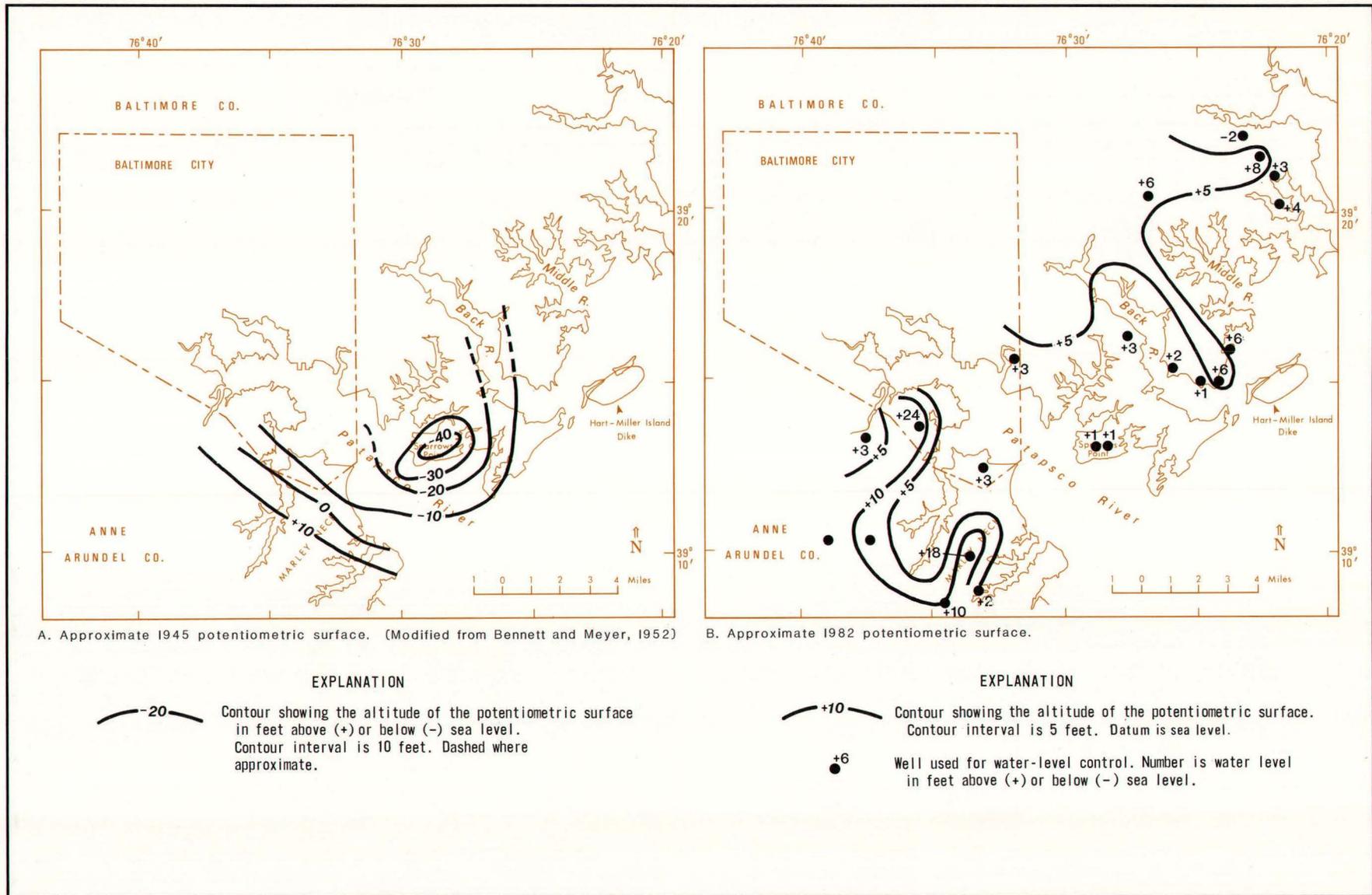
Chloride contamination of the Patapsco aquifer began relatively early in the history of the aquifer. Clark and others (1918, p. 355-364) tabulated the records of several wells in the Patapsco that produced brackish water. By 1945, brackish-water contamination was very severe. Bennett and Meyer (1952, pl. 16) mapped the approximate areal extent of this contamination. This plate is reproduced in modified form in figure 10a. The data show that much of the Dundalk and Fairfield areas were highly contaminated. Because of this contamination, all pumpage of Patapsco water was eventually abandoned in these areas.

The approximate 1982 areal distribution of chloride contamination in the Patapsco aquifer was determined as part of this study. The data, which are shown in figure 10b, show that the present areal extent of chloride contamination is less than in 1945. This suggests that when pumpage from the Patapsco in Baltimore stopped, and the flow system returned to natural conditions, much of the chloride contamination was pushed out of a major part of the aquifer.

Two wells in the Patapsco aquifer were drilled and completed as part of this study. The records of these wells are listed in table 4.

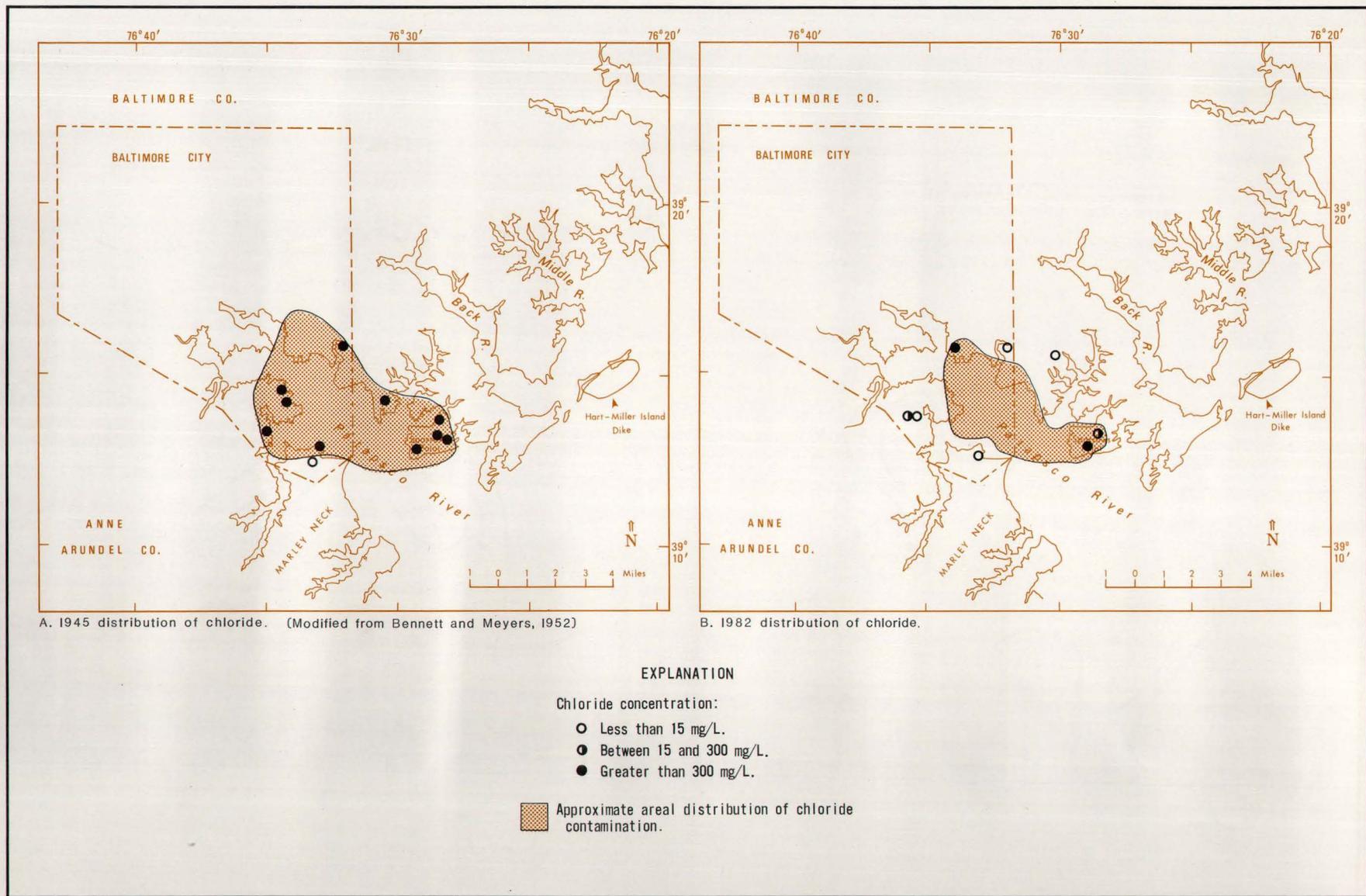
HYDROLOGIC SIGNIFICANCE OF PLEISTOCENE EROSION OF LOWER CRETACEOUS SEDIMENTS

The worldwide lowering of sea level during Pleistocene time has had an impact on the geology of some Coastal Plain sediments. Hack (1957) has shown that during Pleistocene time, the river system in the Chesapeake region approached equilibrium with a sea level about 400 ft below present-day (1982) sea level. In the process of equilibrating with this lowered sea level,



Base map from Bennett, R.R. and Meyer, R.R., 1952

Figure 9.—Approximate 1945 and 1982 potentiometric surfaces of the Patapsco aquifer.



Base map from Bennett, R.R. and Meyer, R.R., 1952

Figure 10.—Areal distribution of chloride contamination of the Patapsco aquifer in 1945 and 1982.

there was considerable downward erosion of Pleistocene river channels. Hack (1957) has shown that in places, these river channels eroded into Cretaceous and Tertiary sediments. The data raise the possibility that such erosion has occurred in the Baltimore area. If so, such erosional channels may significantly impact the hydrology of the Cretaceous aquifer system.

In 1980, construction began on a new highway tunnel under the Baltimore Harbor. Test borings drilled during this construction provide an opportunity to study the effects of Pleistocene erosional channels on Cretaceous sediments. Figure 11 shows two geologic sections that were compiled from test-boring data. These sections demonstrate that the river channels have eroded considerably below the present riverbeds. Following the interpretations of Hack (1957), it is probable that this erosion occurred during Pleistocene low stands of sea level. In geologic section A-A' of figure 11, the ancient channel has breached a significant thickness of the Arundel Formation. In section B-B', the Arundel has been completely breached by the ancient channel.

The channel-fill sediments that were deposited subsequent to the erosive episode consist of gravel-, sand-, and silt-sized material. This material is relatively permeable compared to Arundel Formation sediments. Because of this permeability difference, the channels may act as conduits for brackish-water leakage into the Patuxent aquifer. This problem will be considered quantitatively in the next section of this report.

GENERALIZED HYDROGEOLOGIC FRAMEWORK

In previous sections of this report, the hydrologic properties of Lower Cretaceous sediments have been discussed individually. It is now appropriate to assemble this information into a generalized framework describing the hydrogeology of the Baltimore area.

The subsurface relationships of Lower Cretaceous sediments are shown on plate 2. The Patuxent aquifer crops out in a band adjacent to the Fall Line and dips to the southeast beneath the Chesapeake Bay. Crystalline basement rocks underlie the Patuxent aquifer throughout the study area and serve as a lower confining unit. Where it is overlain by the Arundel Formation, the Patuxent functions as a confined artesian aquifer. The Patapsco Formation overlies the Arundel Formation and crops out in much of the Baltimore area. Where the Patapsco Formation crops out, it functions as an unconfined aquifer.

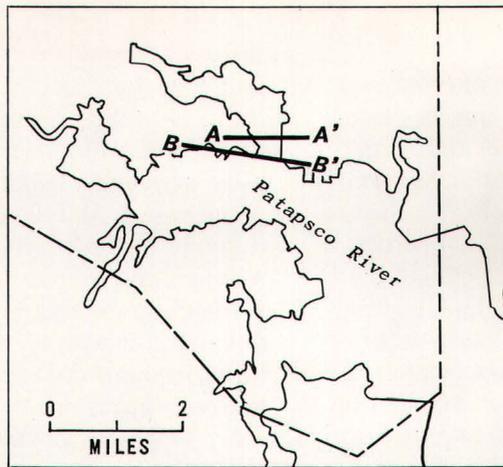
The Patuxent aquifer is recharged directly by atmospheric precipitation in its outcrop area. Much of this incoming water is subsequently discharged from the aquifer by evapotranspiration and by seepage to perennial streams. A small amount of water, however, enters the confined portion of the aquifer and flows down-gradient. Mack and Achmad (written comm., 1984)

estimate that in northern Anne Arundel County, recharge to the confined Patuxent aquifer averages between 1 and 3 in/yr. Fleck (written comm., 1984), using a regional digital simulation of the Coastal Plain sediments in Maryland and Delaware, estimates that recharge to the confined Patuxent aquifer near Baltimore averages about 2 in/yr. Where the hydraulic head in the Patapsco aquifer is higher than the Patuxent, additional recharge to the Patuxent occurs as leakage through the Arundel Formation. Conversely, where Patapsco heads are lower than heads in the Patuxent, water is discharged from the Patuxent. The Arundel Formation is predominantly a clay unit and is much less permeable than either the Patuxent or Patapsco aquifers. However, the Arundel has relatively high porosity and contains large amounts of water in storage.

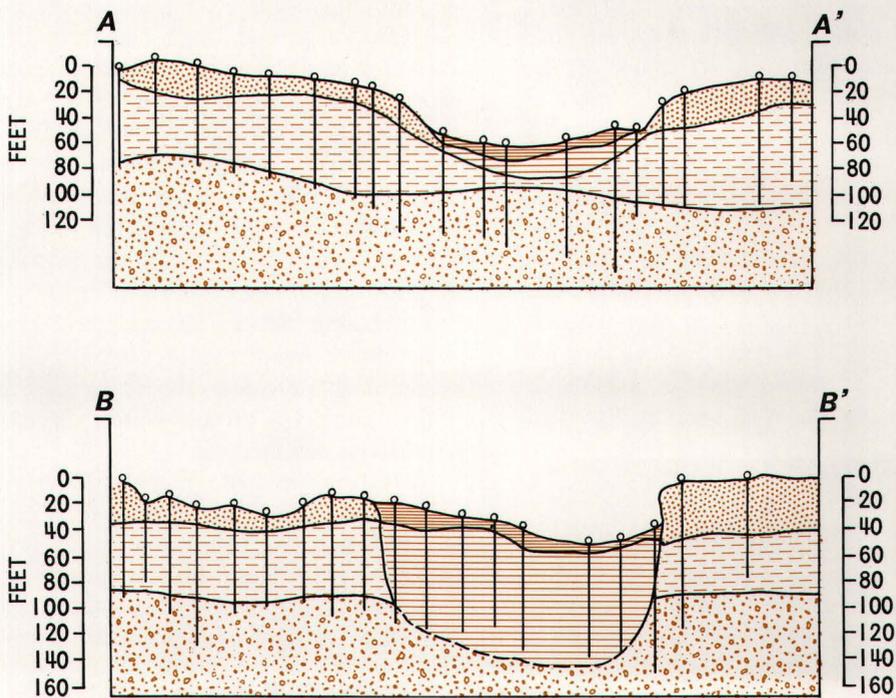
Recharge and discharge from the Patuxent and Patapsco aquifers are strongly influenced by Pleistocene erosional channels. During Pleistocene time, river channels eroded below present-day (1982) sea level and, in places, have truncated Lower Cretaceous sediments (Hack, 1957). For example, the Arundel Formation has been breached in the harbor area of Baltimore City (fig. 11). This has provided a conduit for water to leak out of or into the Patuxent aquifer. Similarly, the Pleistocene Susquehanna River has breached Lower Cretaceous sediments beneath the present Chesapeake Bay. As a result of this erosion, the upper Chesapeake Bay is a major zone of ground-water discharge for Lower Cretaceous sediments.

Natural hydrologic boundaries of the Patuxent aquifer in the Baltimore area coincide with local recharge and discharge areas. The northwestern hydrologic boundary coincides with the outcrop-recharge area. To the northeast and southeast of Baltimore, local hydrologic boundaries are established by ground-water discharge beneath the Chesapeake Bay. In these discharge areas, Patuxent aquifer water levels are maintained near sea level. To the southwest of Baltimore, ground-water discharge into the Patuxent River also establishes a local hydrologic boundary. As a result of these local hydrologic boundaries in the Patuxent aquifer, only a minor component of flow moves from the western side of the Chesapeake Bay to the Delmarva Peninsula (Otton and Mandle, 1984).

The natural flow systems of the Patuxent and Patapsco aquifers have been changed by heavy industrial pumpage over the last 100 years (figs. 6, 7, 9, and table 3). In some areas, water levels in these aquifers were drawn below sea level in response to this pumping stress. This caused brackish water to intrude into the Patapsco aquifer in areas adjacent to the Patapsco River (fig. 10). Because of this contamination, most Patapsco aquifer pumpage near Baltimore has been abandoned and water levels have returned to near prepumping levels (fig. 9).



LOCATION MAP



EXPLANATION

- | | | | |
|---|--|---|---------------------------------------|
|  | Organic - rich mud |  | Sand (PLEISTOCENE) |
|  | Channel - fill silt, sand and gravel (PLEISTOCENE) |  | Test boring used for geologic control |
|  | Arundel Formation | | |
|  | Patuxent Aquifer | | |

Figure 11.—Geologic sections across the Patapsco River near the Canton district.

Over much of the Baltimore area, the Patuxent aquifer is shielded from brackish-water intrusion by the Arundel Formation. However, intrusion has occurred in areas where the Arundel is breached by Pleistocene erosional channels. By 1945, a brackish-water plume

about 4 mi in diameter had developed near the Harbor, Canton, and Fairfield districts of Baltimore City. This brackish-water plume has grown measurably between 1945 and 1982 (fig. 8) and remains a major water-quality problem.

DIGITAL SOLUTE-TRANSPORT MODEL OF THE PATUXENT AQUIFER

Brackish-water contamination of the Patuxent aquifer has been a serious water-quality problem in the Baltimore area since the 1930's. At that time, several production wells in the Harbor and Canton districts located near the Patapsco River began producing water containing up to 4,000 mg/L chloride. The zone of chloride contamination spread rapidly during the late 1930's and early 1940's in response to increasing pumpage. By 1945, a 5 mi wide plume of chloride contamination (fig. 8a) had developed. The contamination plume continued to spread from 1950 through 1982 (fig. 8b), but at a slower rate.

In the past several years, digital solute-transport models have been used to evaluate a variety of ground-water contamination problems. This technique is useful because a properly calibrated model can be used to estimate the future movements of contamination plumes (Konikow, 1977). In this section of the report, the development of a digital solute-transport model of the Patuxent aquifer is described. This model was designed to fulfill two primary functions. The first of these is to evaluate the relative impact of aquifer parameters (for example, transmissivity and dispersivity) on the distribution and movement of chloride contaminants. This type of analysis is useful in that geologic conditions influencing the contamination can be better understood. This information is readily transferable to other locations and can help identify sites where similar problems may or may not be expected to develop. Secondly, the model can be used to estimate the future direction and rate of contamination movement based on alternative scenarios of aquifer use.

THEORETICAL DEVELOPMENT

In this project, the two-dimensional areal solute-transport code developed and documented by Konikow and Bredehoeft (1978) was used. The following discussion is based on the development presented by Konikow and Bredehoeft (1978, p. 4-7).

Two-dimensional flow of ground water in a non-homogeneous, anisotropic aquifer is described by the equation:

$$\frac{\partial}{\partial x_i} (T_{ij} \frac{\partial h}{\partial x_j}) = S \frac{\partial h}{\partial t} + W \quad (1)$$

$i, j = 1, 2$

where:

T_{ij} = transmissivity tensor, L^2/T ;

h = hydraulic head, L ;

S = storage coefficient, (dimensionless);

t = time, T ;

$W = W(x,y,t)$ = volume flux per unit area (positive for outflow, negative for inflow), L/T ; and

x_i, x_j = cartesian coordinates, L .

The two-dimensional areal transport and dispersion of a non-reactive solute in ground water is described by the equation:

$$\frac{\partial (Cb)}{\partial t} = \frac{\partial}{\partial x_i} (bD_{ij} \frac{\partial C}{\partial x_j}) - \frac{\partial}{\partial x_i} (bCV_i) - \frac{C \cdot W}{\epsilon} \quad (2)$$

where:

C = concentration of the dissolved chemical species, M/L^3 ;

D_{ij} = coefficient of hydrodynamic dispersion, L^2/T ;

b = saturated thickness of the aquifer, L ;

- V_i = seepage velocity in x direction, L/T;
 C' = concentration of the dissolved chemical species in a source or sink fluid, M/L³; and
 ϵ = aquifer effective porosity;
 W = volume flux per unit area, L/T.

The coefficient of hydrodynamic dispersion is related to ground-water velocity and aquifer dispersivity by the equation:

$$D_{ij} = \alpha_{ijmn} \frac{V_m V_n}{|V|} \quad (3)$$

where:

- D_{ij} = coefficient of hydrodynamic dispersion, L²/T;
 V_m, V_n = velocity in x and y direction, L/T;
 $|V|$ = magnitude of the velocity, L/T; and
 α_{ijmn} = aquifer dispersivity, L.

Equations 1 and 2 can be coupled to describe the transport of a solute in flowing ground water. Equation 1 computes a head distribution for given boundary conditions. Darcy's equation is then used to compute the velocity vectors required by equation 2. In this manner, equation 2 may be solved for solute concentrations as a function of position and time.

It is not generally possible to obtain analytical solutions to this problem if complex boundary conditions are specified. However, approximate solutions can be found with numerical techniques. The model used in this report employs the method of characteristics to solve the equations. In this approach, the partial differential equation given by equation 2 is not solved directly. Instead, an equivalent system of ordinary differential equations is solved. A complete description of the numerical techniques used by this model is presented by Konikow and Bredehoeft (1978).

Many assumptions must be made in order to apply this code to field problems. These include (Konikow and Bredehoeft, 1978, p. 4):

- (1) Darcy's equation is valid and hydraulic head gradients are the forces driving fluid movement. Solute movements are driven by head gradients and concentration gradients.
- (2) Aquifer porosity and hydraulic conductivity are constant with time, and porosity is uniform in space.
- (3) Chemical reactions do not affect concentrations of the solute.
- (4) Vertical variations of head and concentration are negligible.
- (5) The aquifer is homogeneous and isotropic with respect to the coefficients of longitudinal and transverse dispersivity.

The accuracy with which a natural aquifer system can be simulated depends in large part on how well these assumptions are met. Most aquifer systems are much too complex for such simplification to be perfectly valid. However, if the assumptions are met within acceptable limits, then the simulation can be useful if interpreted carefully.

DESCRIPTION OF THE MODEL

Purpose

In many respects, the manner in which a digital solute-transport model is constructed depends on the questions being asked. It is important, therefore, to clearly define the purpose of the modeling effort. The stated purpose of the model will later be reflected in the grid design, time discretization, and boundary conditions that are selected.

The Patuxent aquifer presently contains a plume of chloride contamination about 5 mi in diameter (fig. 8b) that is centered on the Harbor district. This contamination plume is a serious water-quality problem. From the standpoint of planning future utilization of the Patuxent aquifer near Baltimore, the most important questions about this contamination plume are:

- (1) What are the geological and hydrologic conditions that have led to the contamination?
- (2) In what direction and at what rate will the plume move in the future?
- (3) Can plume movement be affected by changing present pumping patterns and rates?
- (4) Will the plume move toward the large pumping centers in northern Anne Arundel County?
- (5) Can remedial action significantly reduce the present extent of the contamination plume?

It is significant that each of these questions refers to the behavior of the contamination plume as a whole. Thus, the model must be constructed at a large enough scale to be compatible with the relatively large size of

the plume. Furthermore, the scale must be large enough to incorporate regional hydrologic influences outside of the immediate Baltimore area. Conversely, the scale must be small enough to give adequate definition to the boundaries of the plume. Designing the model at a scale compatible with these conflicting needs will result in several limitations. These limitations will be discussed as they arise during model construction.

Conceptual Model

A digital solute-transport model is a mathematical representation of an aquifer system. It is constructed by (1) quantifying the physical and chemical characteristics of the system, and (2) translating these characteristics into a form that can be manipulated by a computer. Because of the complexity of natural aquifer systems, digital models must be constructed from idealized and simplified representations of the actual systems. These simplified versions of natural systems are called conceptual models.

Figure 12 shows schematically the conceptual model used to construct the digital model of the Patuxent aquifer. This conceptual model is an interpretation of geologic and hydrologic information presented previously in this report.

The Patuxent aquifer is considered to be a two-dimensional flow system confined by the underlying basement rocks and by the overlying Arundel Formation. The basement rocks are considered to be completely impermeable. The Arundel Formation is considered to be a leaky confining bed with the amount of leakage controlled by its thickness, vertical hydraulic conductivity, and the head gradient across it. Recharge to the Patuxent aquifer occurs in its outcrop area and by leakage from the Arundel Formation. Discharge occurs by upward leakage under the Chesapeake Bay and its tributaries. In areas where the Arundel Formation has been eroded and replaced by Pleistocene sediments, leakage is greater than where erosion has not occurred. Leakage from areas overlain by fresh-water streams and land is considered to be chloride free. Leakage from areas overlain by the brackish Patapsco River is considered to contain 5,000 mg/L chloride. This value

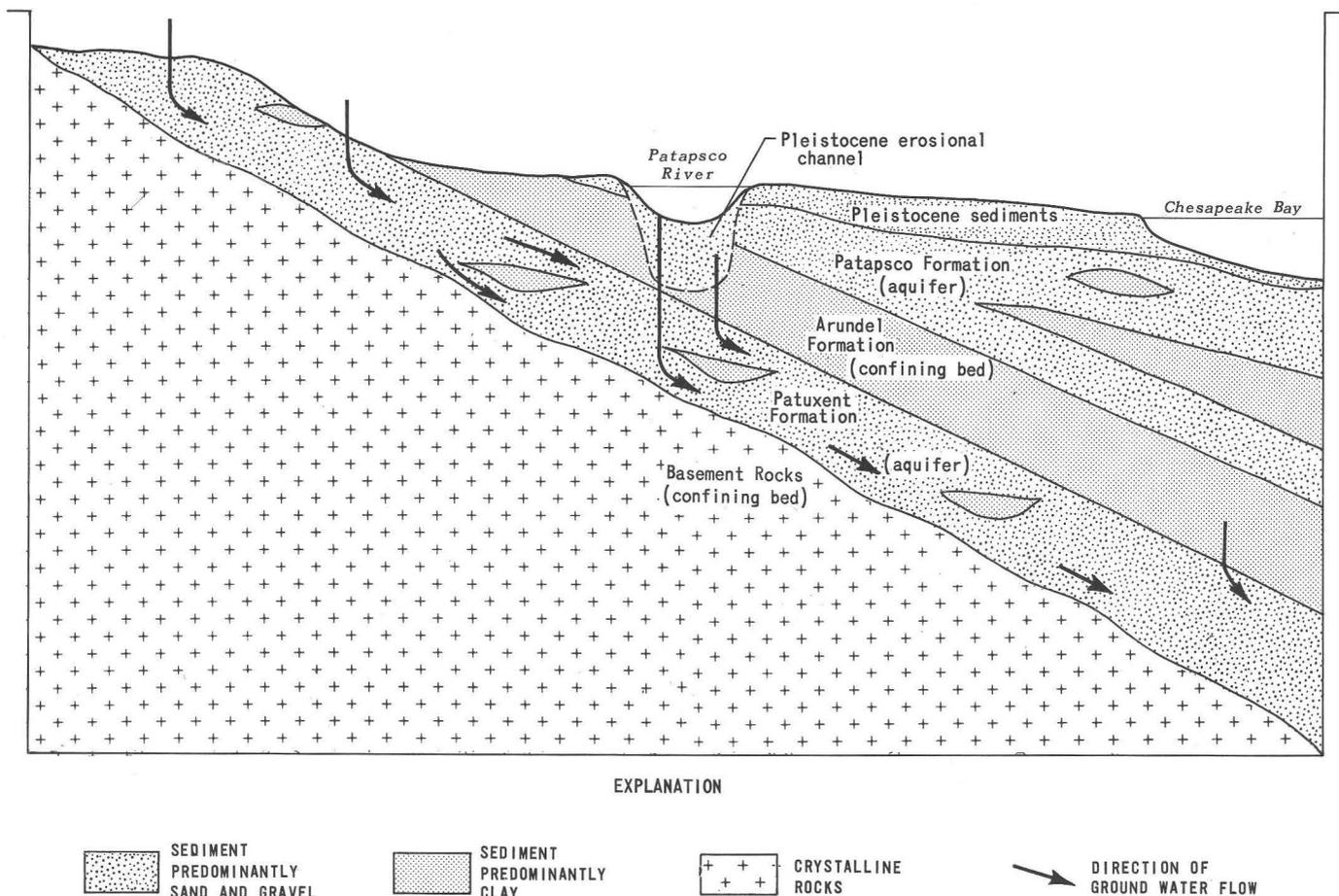


Figure 12.—Conceptual model used in constructing the digital model.

represents the yearly average chloride concentration at the bottom of the Patapsco River (Bricker and others, 1977, p. 48).

This conceptual model is consistent with the main features of the natural flow system. It is also consistent with the distribution and lithology of Lower Cretaceous sediments in the Baltimore area. It must be remembered, however, that this conceptual model is a simplification of the natural system. For example, the exact locations and sizes of clay lenses in the Patuxent Formation are not precisely known. This incorporates uncertainty into the treatment of aquifer transmissivity and aquifer dispersion properties. Also, it is assumed that areal ground-water flow and solute transport in the Patuxent aquifer can be adequately described in two dimensions. That is to say, ground-water flow is predominantly horizontal. However, some vertical variations in head and chloride concentrations can be documented in the Patuxent aquifer. For example, records of wells 3S3E-36, 37, and 39 (table 9, at the end of the report) show that in the Canton area of Baltimore City, heads vary from -8.58 to -4.69 ft, relative to sea level, and chloride concentrations range from 3,500 mg/L to 4,400 mg/L in a 110-ft vertical section of the Patuxent aquifer. Thus, the assumption of two-dimensional flow is a simplification of the natural system.

Grid Design

Several important and sometimes conflicting factors were taken into account in determining the grid design. For example, the modeled area had to be large enough to include the major pumping centers in the Baltimore area. On the other hand, the individual grid blocks had to be small enough to give adequate definition to the contamination plume. Another major consideration dealt with Patuxent aquifer transmissivity. The transmissivity distribution used in the model was determined by flow-net analysis (Bennett and Meyer, 1952, p. 54-58). Ideally, the grid size of the model should be approximately the same scale as the flow net used to determine aquifer transmissivity. Because of the inhomogeneous nature of the Patuxent aquifer, this is of particular importance.

The model area was divided into a square grid of 20 rows and 20 columns. This grid was oriented so that the upper row coincided with the outcrop area of the Patuxent aquifer. Each grid block represents an area of 0.57 mi² and this scale is roughly compatible with the flow-net analysis of Bennett and Meyer (1952). By convention, the point at the center of each block is called the node. The nodes are labeled in the same manner as an x-y coordinate system. For example, the index for node 5-8 refers to the center of the grid block that is located in row 5 (from the left), column 8 (from the

top). Each input value to the node (transmissivity, leakage, and so forth) is considered to be the average value over the entire block. The grid design for the solute-transport model is shown in figure 13.

Model Boundaries

Once the model grid had been developed taking into account the hydrologic framework, the next step was to apply appropriate boundary conditions to the modeled area. The model boundaries were designed to simulate, as closely as was feasible, the natural boundaries of the hydrologic system.

The northwest boundary of the grid coincides with the outcrop area of the Patuxent aquifer. This boundary was modeled as a constant-head boundary (that is, heads are not allowed to vary). This treatment is appropriate because it has been documented that outcrop area wells are not affected by heavy aquifer pumpage (Bennett and Meyer, 1952, p. 96).

The three other grid boundaries do not coincide with the natural hydrologic boundaries of the aquifer. About 5 mi northeast and southeast of the grid area, natural hydrologic boundaries are located in discharge areas beneath the Chesapeake Bay. About 5 mi southwest of the grid area, a natural hydrologic boundary is located beneath the Patuxent River. In order to simulate the lateral extent of these natural hydrologic boundaries beyond the grid area, a head-dependent flux (HDF) condition was used at the grid boundaries (Hutchinson and others, 1981). In this approach, lateral ground-water flow is allowed across the edge of the model grid. The amount of this flow depends on the head at the grid boundary, which is calculated by the model, and the head at the lateral hydrologic boundary, which is assumed to remain constant. During simulation, therefore, boundary flow will vary in response to head changes at the boundary grid blocks.

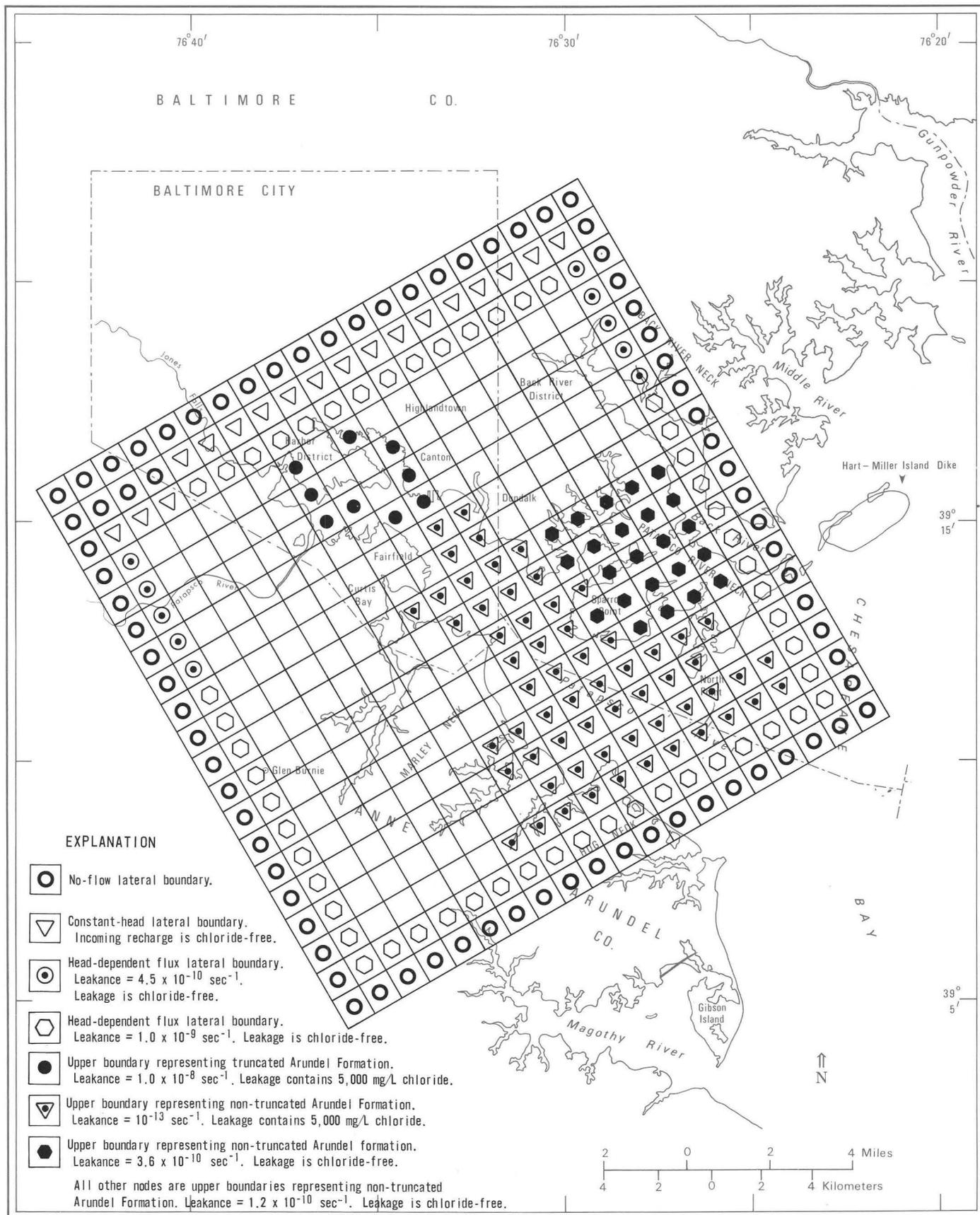
The HDF boundary condition is based on the one-dimensional equation describing ground-water flow under steady-state conditions. For a leaky artesian aquifer (such as the Patuxent aquifer), this equation may be written as:

$$T \frac{\partial^2 h}{\partial x^2} - \frac{K}{b} (h-H) = 0 \quad (10)$$

where:

T = aquifer transmissivity, L²/T;

x = lateral distance from the grid boundary, L;



Base map from the Maryland Geological Survey County Topographic Map Series, 1:62,500

Figure 13.—Grid design and boundary conditions used in the digital model.

K = vertical hydraulic conductivity of the confining bed, L/T ;

b = thickness of the confining bed, L ;

L = lateral distance to the constant-head boundary, L ;

h = altitude of the potentiometric surface, L ; and

H = altitude of the overlying water table and altitude of potentiometric surface at the constant-head boundary, L .

To obtain an analytical solution to equation 10, it is assumed that a constant-head boundary is located at a distance L outside the grid boundary. Under this assumption, equation 10 is subject to boundary conditions of:

$$h = H \text{ at } x = L$$

$$h = h_0 \text{ at } x = 0 \quad (10a)$$

Solving equation 10 with these boundary conditions and applying Darcy's equation at the grid boundary yields:

$$\Delta x q_0 = -T(H-h_0) \sqrt{\lambda} \frac{(1+e^{-2L} \sqrt{\lambda})}{(1-e^{-2L} \sqrt{\lambda})} \quad (11)$$

where:

$$\sqrt{\lambda} = \sqrt{\frac{K}{bT}}, L^{-1};$$

q_0 = discharge per unit width of aquifer, L/T ;

Δx = width of grid block, L .

Solving equation 11 for q_0 and defining a constant C as:

$$C = \frac{T \sqrt{\lambda}}{\Delta x} \cdot \frac{(1+e^{-2L} \sqrt{\lambda})}{(1-e^{-2L} \sqrt{\lambda})} \quad (11a)$$

gives:

$$q_0 = -C(H-h_0). \quad (11b)$$

The constant C has units of T^{-1} and is exactly analogous to leakage.

In order to apply the HDF approach, the following assumptions must be made:

- (1) Aquifer transmissivity between the grid boundary and the constant-head boundary is constant.
- (2) Ground-water flow between the grid boundary and the constant-head boundary is steady-state.
- (3) Thickness and vertical hydraulic conductivity of the overlying confining bed are constant between the grid boundary and the constant-head boundary.

In addition to these general assumptions, applying the computer code of Konikow and Bredehoeft (1978) without modification requires the following considerations:

- (1) The head value input for the water table at the model boundary node equals the head in the aquifer at the constant-head boundary.
- (2) Vertical leakage through the confining bed at the grid boundary is negligible.

With these considerations, the C constant (eq. 11a) may be substituted for leakage in the boundary grid blocks. The "leakage" calculated at the grid boundary by the model then represents the lateral flux from the distant constant-head boundary.

It is evident from the development of the HDF approach that the required assumptions will only approximate the natural hydrologic framework of the Patuxent aquifer. For example, it can be documented that the transmissivity between the grid boundary and the hydrologic boundaries is not always constant. Also, the assumption of steady-state ground-water flow outside of the grid area is approximate. Finally, the assumption that heads in the discharge areas remain constant is also approximate. Despite these simplifications, it was judged that the HDF approach was a better approximation of the natural hydrologic system than assuming either constant-head or no-flow conditions at the model-grid boundary.

The following procedures were used to apply the HDF approach in the digital solute-transport model:

- (1) The hydrologic discharge-recharge boundaries that are located beneath the Chesapeake Bay and beneath the Patuxent River were assumed to be constant-head boundaries.
- (2) The lateral distance from the grid boundary to each constant-head boundary was estimated.

- (3) The approximate transmissivity of the aquifer between the grid and the constant-head boundary was estimated.
- (4) The thickness and vertical hydraulic conductivity of the overlying confining bed (the Arundel Formation) between the grid and the constant-head boundary was estimated.

Based on these estimates, a C constant was calculated using equation 11a for each grid block on the grid boundary. For example, if L equals 26,400 ft (5 mi), K equals 10^{-11} ft/s, T equals 0.047 ft²/s ($\approx 4,000$ ft²/d), and b equals 150 ft, equation 11a yields a C value of 4.5×10^{-10} sec⁻¹. Values of C calculated in this manner were then substituted for leakance values in the grid blocks along the northeast, southeast, and southwest boundaries of the model. In practice, grid blocks representing updip areas of the Patuxent aquifer were assigned a value of 4.5×10^{-10} sec⁻¹. Grid blocks representing downdip areas of the Patuxent were assigned a value of 1.0×10^{-9} sec⁻¹. The higher C values in the downdip grid blocks reflect the increasing aquifer transmissivity in that direction. In all cases, the distance L to the constant-head boundaries was taken as 5 mi. Because of uncertainties in defining the parameters required by equation 11a, further refinement of the C values was not judged to be meaningful. The locations and C values of HDF nodes used in the model simulations are shown in figure 13.

The HDF boundary condition also requires use of proper initial conditions in the model simulations. It was specified that each constant-head boundary was maintained at sea level. In addition, it was specified that the water table remained at sea level throughout the simulations. This was done so that the boundary condition $h = H$ (eq. 10a) was satisfied. However, these conditions also represent a simplification of the natural system. For example, figure 9 shows that Patapsco aquifer heads (that is, the water-table heads) in 1982 actually range between 0 and 10 ft above sea level over much of the project area. However, because historical drawdowns in the Patuxent aquifer were large (up to 150 ft) compared to this range, this was considered an acceptable approximation. Figure 9 also shows that Patapsco aquifer water levels have changed through time as a result of pumpage. It is not possible to simulate water-table head changes with the two-dimensional model used in this study. Thus, assuming constant water-table heads also represents a simplification of the natural hydrologic system.

In addition to lateral boundaries, upper and lower boundaries must also be specified for the model. The lower boundary, which coincides with the basement rocks (fig. 12), was modeled as no-flow. The upper boundary, which coincides with the Arundel Forma-

tion, was modeled as a leakage boundary. The actual amount of leakage through the upper boundary is calculated by the model in a manner similar to calculation of head-dependent lateral flux. This calculation is based on the head difference across the confining bed (calculated by the model) and on the leakance of the confining bed. Figure 13 shows the locations of upper boundary leakage nodes. Leakance values used in the model are discussed in the section on Leakance of the Upper Confining Bed.

Transmissivity and Storage Coefficient

Values of transmissivity and storage coefficient for the Patuxent aquifer are discussed in the Hydrogeology section of this report. The transmissivity distribution of the Patuxent aquifer near Baltimore is shown in figure 5. Average transmissivity values for each grid block were estimated by overlaying the grid onto figure 4. The values were then entered into the model as a matrix. A storage coefficient of 1.0×10^{-4} is representative of the confined portions of the Patuxent and was used throughout the modeled area.

Starting Heads

The approximate prepumping potentiometric surface of the Patuxent aquifer was estimated from historical water levels (fig. 6a). The average head values for each grid block were estimated from figure 6a and used as starting heads for model simulations. During calibration, the model was first adjusted so that it could reproduce the approximate prepumping surface under conditions of no stress. This was done so that simulations would start from steady-state conditions.

Historical records of the first wells in the Patuxent aquifer do not record any evidence of chloride contamination. Under natural conditions, water would be expected to discharge from the aquifer to the Patapsco River. For these reasons, calibration simulations specified that no chloride was present initially in the aquifer.

Leakance of the Upper Confining Bed

Leakance is defined as the ratio of vertical hydraulic conductivity to confining-bed thickness. The approximate thickness of the Arundel Formation, which serves as the upper confining bed to the Patuxent aquifer, is shown in figure 3. Some estimates of the vertical hydraulic conductivity are available from the literature (Mack and Achmad, in prep.). Values for this property obtained by direct measurement are not available. Thus, it was not possible to precisely evaluate the leakance of the Arundel Formation. For this study, leakance values for each grid block were determined during calibration

of the model. In all cases, vertical hydraulic conductivities suggested by model calibration fall within the range reported in the literature (10^{-9} – 10^{-11} ft/s).

Porosity and Dispersivity

Because the model calculates ground-water velocity based on Darcy's equation, it is necessary to know the average effective porosity (interconnected pore spaces) of the aquifer. The effective porosity of the Patuxent aquifer near Baltimore was estimated on the basis of gamma-gamma density and neutron-density geophysical logs. A gamma-gamma log is obtained by emitting gamma radiation into the formation, and then measuring the amount of radiation that is backscattered. The amount of backscattering is proportional to the density and, therefore, total porosity of the formation. In a predominantly unlithified aquifer such as the Patuxent, total porosity is approximately equal to the effective porosity. A neutron-density log measures the moisture content of the surrounding formation. If the formation is under saturated conditions, this gives a measure of the effective porosity of the formation.

A gamma-gamma log of well 3S5E-46 in Baltimore City indicated an effective porosity of about 38 percent for the Patuxent Formation. A neutron log of this same well yielded an effective porosity of 33 percent. Gamma-gamma and neutron-density logs of well 3S2E-5 in Baltimore City indicated very similar values of porosity. On the basis of this data, a porosity value of 35 percent was considered representative of the modeled area and was used in the model.

No attempt was made to measure dispersivity values for the Patuxent aquifer. Values for this property were estimated during calibration of the model.

Sensitivity Analysis

Prior to calibrating the solute-transport model, a series of simulations were made to determine the model's sensitivity to various hydrologic properties. This analysis was made in order to facilitate the calibration process and to gain a better understanding of the hydrologic system.

The results of 14 sensitivity analysis model simulations are summarized in table 5. Each run simulated a period of 50 years and began from steady-state conditions. Hypothetical pumping centers were simulated in the Harbor district (node 10-5, 0.9 Mgal/d; and node 9-5, 1.5 Mgal/d), and in the Canton district (node 12-6, 1.8 Mgal/d). The aquifer was considered to be initially chloride-free. Aquifer parameters used in the runs were selected only for comparative purposes.

The sensitivity analysis demonstrates several important characteristics of the model:

- (1) The ground-water flow portion of the model is most sensitive to aquifer transmissivity and vertical hydraulic conductivity of the overlying confining bed.
- (2) The flow model is relatively insensitive to the elevation of constant-head boundaries and storage coefficient.
- (3) The solute-transport portion of the model is most sensitive to leakage of confining beds, aquifer transmissivity, and aquifer dispersivity.
- (4) The solute-transport portion of the model is relatively insensitive to the transverse-longitudinal dispersivity ratio, aquifer porosity, and elevation of constant-head nodes.

Model Calibration

Before a model can be used to predict the future behavior of an aquifer system, the model's ability to reproduce historical behavior must be verified. Although the best available information is used in model construction, these parameters often have to be adjusted before the model accurately reproduces historical behavior. The process of adjusting model parameters in this manner is termed "calibration". Calibrating a digital solute-transport model must be accomplished in two distinct steps. First, the ground-water flow portion of the model must be calibrated with historical pumpage and water levels. When this phase of calibration is complete, the solute-transport portion of the model may be calibrated with available historical water-quality data.

The exact procedures followed during model calibration are largely determined by the kinds of available historical data. In the Baltimore area, very little water level or pumpage data were recorded prior to the year 1900. For the period 1900–40, however, a large number of water levels obtained in the Canton, Fairfield, and Sparrows Point districts were recorded by Geyer (1945, p. 37–41). Many of these water levels were obtained from wells screened in the Patuxent aquifer. Subsequent to Geyer's (1945) study, Bennett and Meyer (1952) prepared a potentiometric map of the Patuxent for the year 1945 (fig. 6b). Also available is a hydrograph of well 2S5E-1 for the period 1943–82. This well is located near several pumping centers (see pl. 1 for well location). In addition, the 1982 potentiometric surface of the Patuxent was measured as part of this study (fig. 7). In addition to this water-level data, the areal distribution of chloride contamination in 1945 was mapped by Bennett and Meyer (1952, fig. 8a). The distribution of chloride

Table 5.—Aquifer and confining-bed characteristics used in the sensitivity analysis of solute-transport model

[Period of simulation = 50 years
Pumpage = 4.2 Mgal/d from 3 nodes]

Sensitivity analysis run no.	Aquifer parameters						Confining bed parameters		Results						Comments
	Porosity	Transmissivity (ft ³ /s)	Storage coefficient (dimensionless)	Longitudinal dispersivity (ft)	Ratio of transverse to longitudinal dispersivity	Elevation of constant head nodes (ft)	Leakance of undisturbed Arundel Clay ₁ (sec ⁻¹)	Leakance of eroded Arundel Clay ₁ (sec ⁻¹)	Chemical mass balance error (percent)	Flow model mass balance error (percent)	Drawdown at pumped node (ft)	Net leakage (ft ³ /s)	Maximum computed Cl ⁻ concentration (mg/L)	Area of Cl ⁻ contamination (mi ²)	
1	0.30	matrix	10 ⁻⁴	100	0.3	matrix	10 ⁻¹³	10 ⁻⁸	-10.1	<1	30	6.55	3,769	16.3	Standard run. Parameters arbitrarily chosen.
2	.40	do.	10 ⁻⁴	100	.3	do.	10 ⁻¹³	10 ⁻⁸	-10.1	<1	30	6.55	3,569	14.0	Shrinks plume of chloride contamination.
3	.30	X2	10 ⁻⁴	100	.3	do.	10 ⁻¹³	10 ⁻⁸	-27.0	<1	13	6.55	2,101	12.9	Reduces drawdown and reduces amount of chloride leaking into aquifer.
	.30	÷2	10 ⁻⁴	100	.3	do.	10 ⁻¹³	10 ⁻⁸	- 2.0	<1	60	6.55	4,493	16.3	Increases drawdown and increases amount of chloride leaking into aquifer.
4	.30	matrix	10 ⁻⁴	1,000	.3	do.	10 ⁻¹³	10 ⁻⁸	-13.0	<1	30	6.55	3,731	26.4	Increases plume of chloride contamination. Gradual concentration gradient.
5	.30	do.	10 ⁻⁴	10	.3	do.	10 ⁻¹³	10 ⁻⁸	-14.0	<1	30	6.55	4,169	12.4	Shrinks plume of chloride contamination. Very sharp concentration gradient.
6	.30	do.	10 ⁻⁴	100	.1	do.	10 ⁻¹³	10 ⁻⁸	-14.0	<1	30	6.55	4,128	16.9	Virtually identical to standard run.
7	.30	do.	10 ⁻⁴	100	.8	do.	10 ⁻¹³	10 ⁻⁸	-14.0	<1	30	6.55	4,128	16.9	Virtually identical to standard run.
8	.30	do.	10 ⁻⁴	100	.3	do.	10 ⁻¹³	10 ⁻¹⁰	+ .5	<1	39	6.55	347	10.69	Decreases chloride concentrations; shrinks contaminated area.
9	.30	do.	10 ⁻⁴	100	.3	do.	10 ⁻¹³	10 ⁻⁶	-14.0	<1	27	6.55	4,679	15.8	Increases maximum computed chloride concentration.
10	.30	do.	10 ⁻⁴	100	.3	do.	10 ⁻¹⁵	10 ⁻⁸	-14.0	<1	30	6.55	4,125	15.8	Virtually identical to standard run.
11	.30	do.	10 ⁻⁴	100	.3	do.	10 ⁻¹¹	10 ⁻⁸	-14.0	<1	30	6.55	4,124	27.0	Plume of chloride contamination too large.
14	.30	do.	10 ⁻⁴	100	.3	÷2	10 ⁻¹³	10 ⁻⁸	- 4.7	<1	32	6.55	4,477	18.56	Small increase in drawdown of pumped nodes increase chloride leakage into aquifer.
15	.30	do.	10 ⁻⁵	100	.3	matrix	10 ⁻¹³	10 ⁻⁸	- 8.6	<1	30	6.55	3,715	16.3	Increases rate but not amount of drawdown.
16	.30	do.	10 ⁻³	100	.3	do.	10 ⁻¹³	10 ⁻⁸	- 8.6	<1	30	6.55	3,957	16.3	Decreases rate but not amount of drawdown.

contamination in 1982 was mapped as part of the present study, and is shown in figure 8b.

It was judged that the 1900–40 water levels, the 1943–82 hydrograph of well 2S5E-1, the measured potentiometric surface in 1945, and the measured potentiometric surface in 1982 were the best available data for calibrating the ground-water flow portion of the model. Also, it was determined that the measured chloride distributions in 1945 and 1982 were the best available data for calibrating the solute-transport portion of the model.

In order to simulate the pumping history of the Patuxent aquifer, the simulation period (1850 to 1982) was divided into 19 discrete pumping periods. The year 1850 was chosen to start the simulation period because little water was being pumped at that time and near pre-pumping conditions prevailed. The pumping periods, which are listed in table 3, were chosen so as to coincide with significant changes in pumping patterns.

The sensitivity analysis (table 5) indicated that the ground-water flow portion of the model is most sensitive to aquifer transmissivity and confining-bed leakance. However, because the Patuxent aquifer transmissivity is relatively well documented, it was not varied during calibration. The leakance of the Arundel Formation, which is much less certain, was varied on a trial-and-error basis to calibrate the model. It was found that relatively high leakance values had to be assigned to nodes representing the Patapsco River near the Harbor district to obtain an acceptable match. In this area, it has been documented that Pleistocene channels eroded into the Arundel Formation and deposited more permeable silts and sands (fig. 11). Because of this geologic evidence, the higher leakance values in this area are justified. The ground-water flow portion of the model was considered calibrated when the following four criteria were satisfied:

- (1) Simulated water levels for the period 1900–45 matched observed water levels within a 20-ft margin of error. This error margin is equivalent to about 15 percent of the maximum observed drawdown during the calibration period.
- (2) The configurations of the 1945 and 1982 potentiometric surfaces were reproduced.
- (3) Simulated water levels matched the hydrograph of well 2S5E-1 with a 20-ft margin of error. This error margin is equivalent to about 15 percent of the maximum observed drawdown during the calibration period.
- (4) A graph of simulated versus measured 1982 water levels resulted in an acceptable statistical match to the equation $y = mx + b$, where $x =$ measured and $y =$ simulated water

levels. The match was considered acceptable when the y intercept of the regression line was 0.0 ± 5 ft, when the slope of the line was 1.0 ± 0.1 , and when r^2 for the regression was greater than 0.80.

Because of uncertainties in the water-level and pumpage data, further refinement was not judged to be meaningful. The final match between measured and simulated water levels during the period 1900–41 is shown in figure 14. The simulated 1945 and 1982 potentiometric surfaces are shown in figure 15. The match between simulated water levels and the hydrograph of well 2S5E-1 is shown in figure 16a. Finally, the statistical match between simulated and measured 1982 water levels is shown in figure 16b.

After an acceptable match was obtained between measured and simulated water levels, the model-

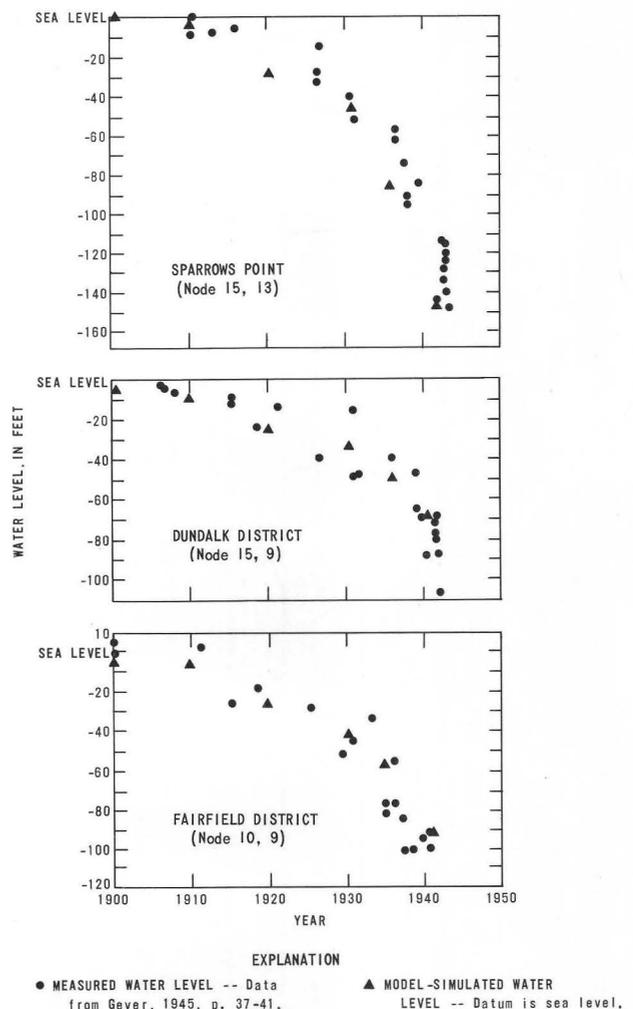
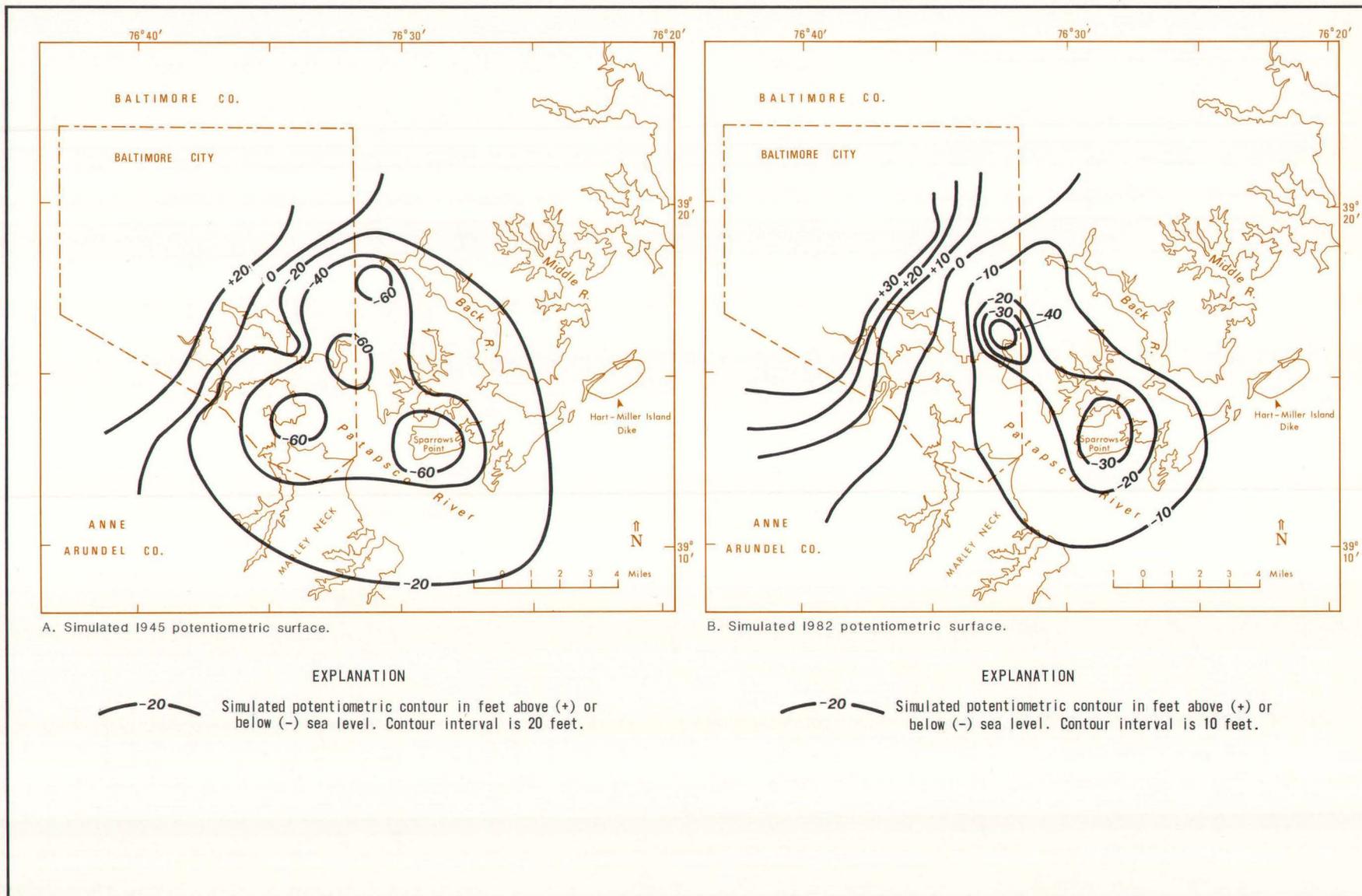


Figure 14.—Comparison of simulated and measured water levels for the period 1900–41.



Base map from Bennett, R.R. and Meyer, R.R., 1952

Figure 15.— Simulated 1945 and 1982 potentiometric surfaces of the Patuxent aquifer.

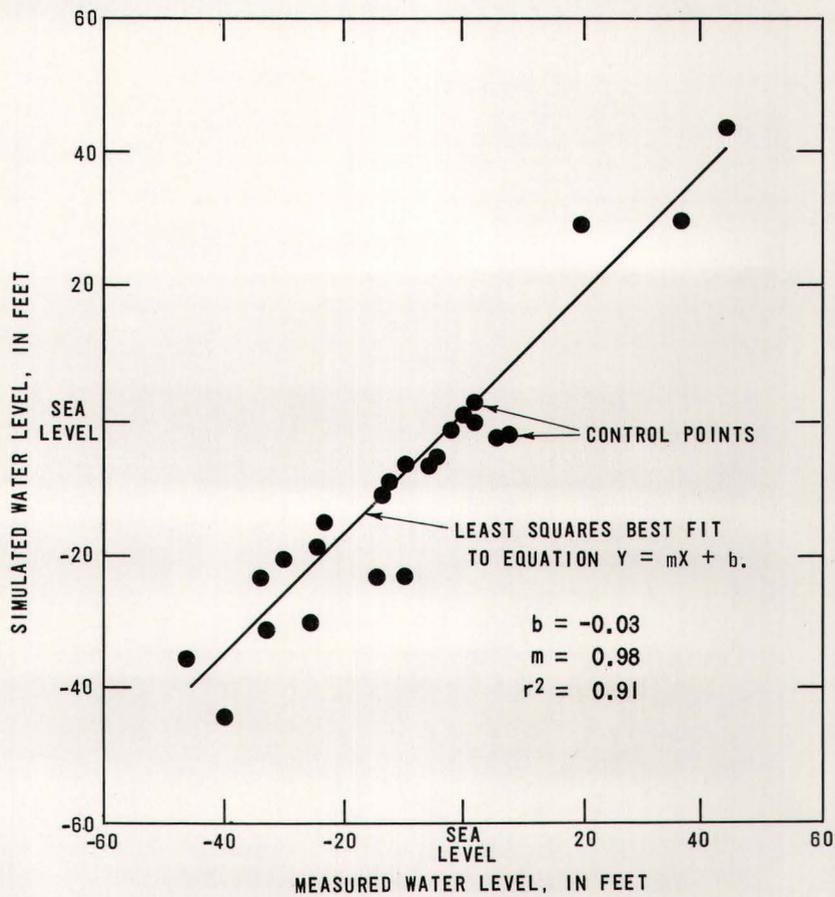
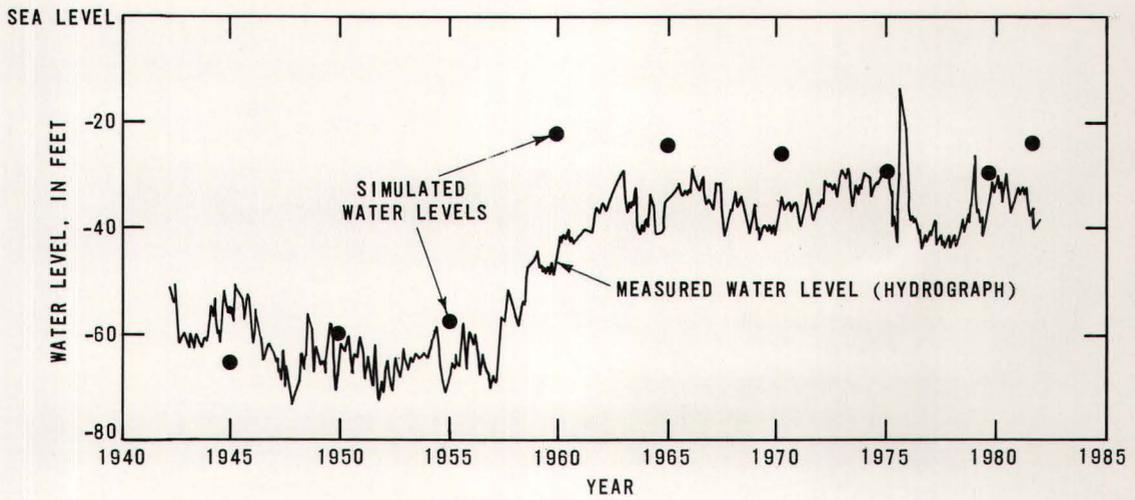


Figure 16.—Comparison of simulated water levels with a hydrograph of well 2S5E-1 and comparison of simulated and measured 1982 water levels.

calculated water budget was used to provide a rough check on the model solution. Previous studies (Mack and Achmad, 1984, written comm.; Fleck, 1984, written comm.) indicated that between 1 and 3 in. of water per year recharge the Patuxent aquifer in the Baltimore area. The digital model used in this study calculated an average recharge rate of 1.98 in/yr for the entire calibration period. This agrees well with the results of previous studies and indicates that the simulated water budget, and thus the model solution, is reasonable.

Once an acceptable calibration of the flow model was obtained, the next step was to calibrate the solute-transport portion of the model. The data used for this calibration were the measured chloride distributions in 1945 and 1982 (fig. 8). This phase of calibration was accomplished by further refinement of confining-bed leakance values and adjustment to aquifer dispersivity. The simulated water levels shown in figures 14, 15, and 16 include the results of this phase of model calibration. It was found that relatively low leakance values of 10^{-13} sec^{-1} were required for nodes representing the non-truncated Arundel Formation overlying the brackish Patapsco River. Specifying leakance values greater than 10^{-13} sec^{-1} in the simulations resulted in chloride entering the aquifer in the Sparrows Point district where no such contamination has been documented. However, because storage of fresh water in confining beds is not considered by the model used in this report, these leakance values may be artificially low.

After adjustments of confining-bed leakance were complete, aquifer dispersivity was varied on a trial-and-error basis. It was found that the most reasonable match was obtained with a dispersivity of 100 ft. The model was considered calibrated when the area of simulated chloride plume matched the measured area within 10 percent. The computed 1945 and 1982 chloride distributions are shown in figure 17. Note that the model duplicates reasonably well the 1 to 1½ mi southeast movement of the plume from 1945 to 1982 that is documented in figure 8.

SIMULATIONS OF FUTURE CHLORIDE MOVEMENT

After calibration, the solute-transport model was used to simulate the future movement of the chloride contamination plume. Each of the simulation scenarios were selected in response to information requests from the Maryland Geological Survey or from the Maryland Water Resources Administration. It should be emphasized at this point that the results of each simulation are subject to various uncertainties. These uncertainties arise from the assumption inherent in the modeling process, simplifications made in conceptualizing the

natural system, and limited data available for model calibration. Thus, the simulations of future movement should be regarded as estimates only.

The simulations made for this report consist of the following:

- (1) A simulation that continues 1982 rates of pumpage for 50 years.
- (2) A 50-year simulation that doubles the 1982 Sparrows Point pumpage and keeps all other pumpage at 1982 rates.
- (3) A 50-year simulation that assumes all pumpage in the Baltimore area is discontinued.
- (4) A 50-year simulation that assumes 1982 rates of pumpage continue in Baltimore, but that a cone of depression 100 ft below sea level exists near Glen Burnie, Anne Arundel County.
- (5) A 50-year simulation that continues 1982 pumpage rates plus 5-Mgal/d additional pumpage in Marley Neck, Anne Arundel County.
- (6) A 50-year simulation of pumpage and fresh-water injection in Marley Neck, Anne Arundel County.

These simulations are designed to illustrate the probable motion of the chloride plume given possible future pumping patterns.

Simulation 1

This simulation illustrates chloride movement assuming that the average 1982 pumping rate continues for a 50-year period beginning in 1982. The 1982 chloride distribution was used as the initial condition for this simulation. Figure 18 shows the predicted potentiometric surface and areal distribution of chloride contamination at the end of the simulation period. The total area of chloride contamination in 1982 was about 30 mi^2 . At the end of this 50-year simulation, the area of contamination increased only to 31 mi^2 . The plume is predicted to shift slightly to the south (toward the pumping center at Sparrows Point), but the movement is very slow. This simulation seems to indicate that the chloride plume is nearly stabilized with respect to 1982 pumpage. The virtual lack of predicted movement suggests that present (1982) cones of depression are restricting further down-dip movement of the chloride plume.

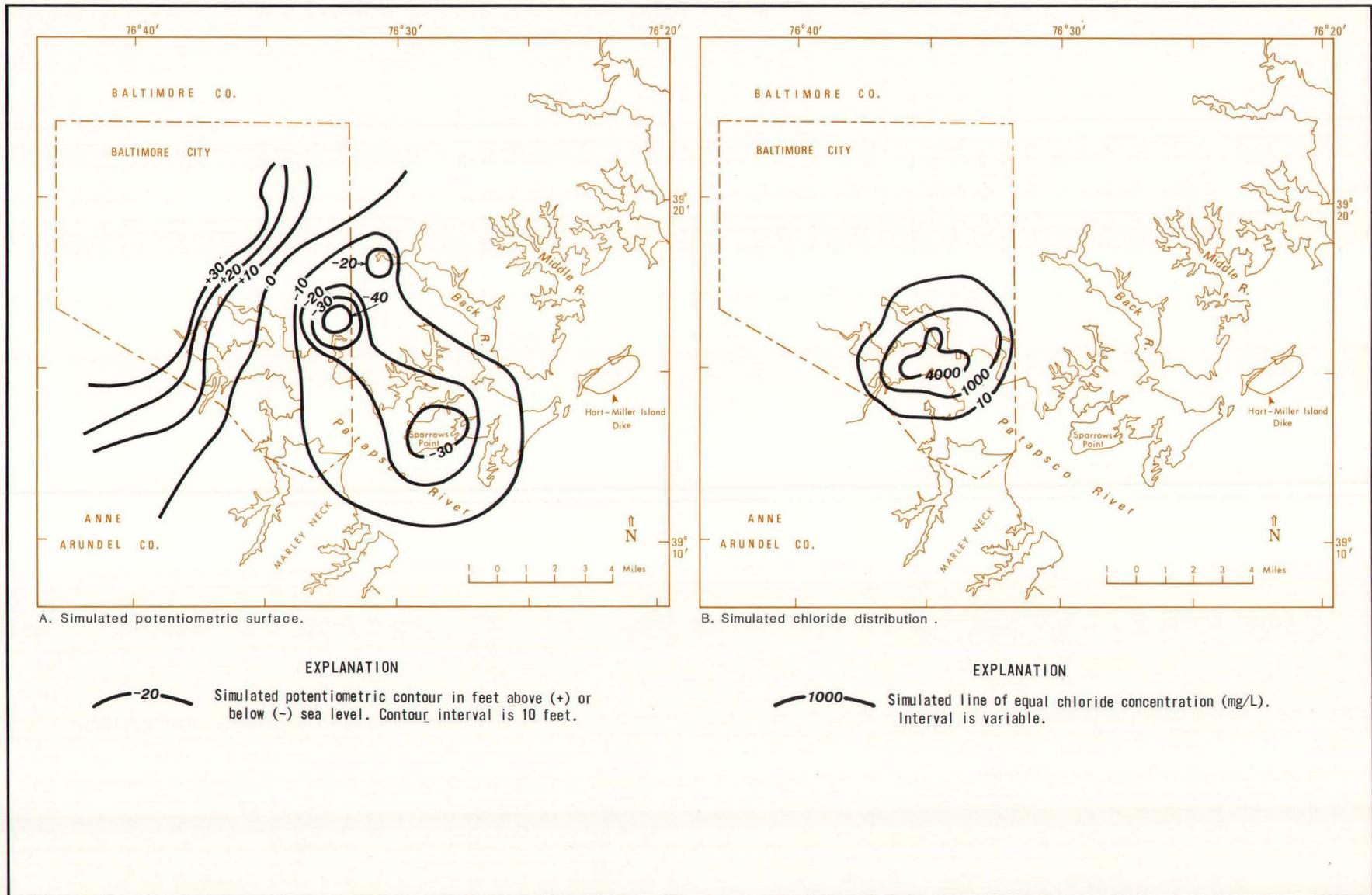
Simulation 2

The Bethlehem Steel Plant at Sparrows Point is presently (1982) the single largest user of water from the Patuxent aquifer. The results of simulation 1 suggest



Base map from Bennett, R.R. and Meyer, R.R., 1952

Figure 17.—Simulated 1945 and 1982 chloride distributions of the Patuxent aquifer.



Base map from Bennett, R.R. and Meyer, R.R., 1952

Figure 18.—Simulated potentiometric surface and chloride distribution assuming 1982 pumping rates continue for 50 years.

that 1982 pumpage rates for 50 years will result in little downdip movement of the contamination plume. Simulation 2 was designed to estimate plume movement if Sparrows Point pumpage was to increase substantially. For the purposes of this simulation, it was assumed that other Baltimore area pumpers maintained 1982 pumpage rates, while pumpage at Sparrows Point was doubled (to 9.78 Mgal/d). The chloride distribution in 1982 was used as the initial condition for this simulation. The results are shown in figure 19. A cone of depression about 60 ft below sea level is predicted as a result of this pumpage. The total area of chloride contamination at the end of the simulation period is predicted to increase from 30 to 34 mi². This predicted increase results from the chloride plume shifting towards Sparrows Point between 1/2 and 1 mi. Much of this movement, however, is predicted to occur under the Patapsco River. On the basis of this simulation, it can be concluded that the chloride plume will not reach Sparrows Point in the foreseeable future, even if pumpage there is substantially increased.

Simulation 3

In many instances of brackish-water contamination of fresh-water aquifers, one way to reverse the intrusion is to cut pumpage substantially. Simulation 3 was designed to estimate the plume behavior if all pumpage from the Patuxent aquifer was stopped. This simulation was made for a period of 50 years using the chloride distribution in 1982 as the initial condition. The results of this simulation are shown in figure 20. The flow system returns to prepumping conditions, as would be expected. The total area of chloride contamination actually increased slightly from 30 to 31 mi². This suggests that stopping Patuxent pumpage would not significantly reduce the chloride contamination problem.

It should be noted that the predicted response of Patuxent aquifer chloride contamination to the cessation of pumpage is significantly different than the observed behavior of the overlying Patapsco aquifer. Between 1945 and 1982, the Patapsco aquifer returned to very near prepumping conditions (fig. 9). During this period, there was a measurable shrinkage of chloride contamination in the Patapsco aquifer. The question may reasonably be asked, "Why is the predicted behavior of the Patuxent so much different than the observed behavior of the Patapsco aquifer?". The probable answer to this question deals with the relationship of each aquifer to its overlying confining bed. Chloride is drawn into the Patuxent aquifer where the Arundel Formation has been breached by Pleistocene channels (fig. 11). As the chloride moves downgradient, it is confined by the Arundel Formation and cannot easily escape. The Patapsco Formation, on the other

hand, does not have an overlying confining bed in much of the Baltimore area. Thus, when gradients reversed, the chloride could be flushed out of the aquifer as easily as it entered.

Simulation 4

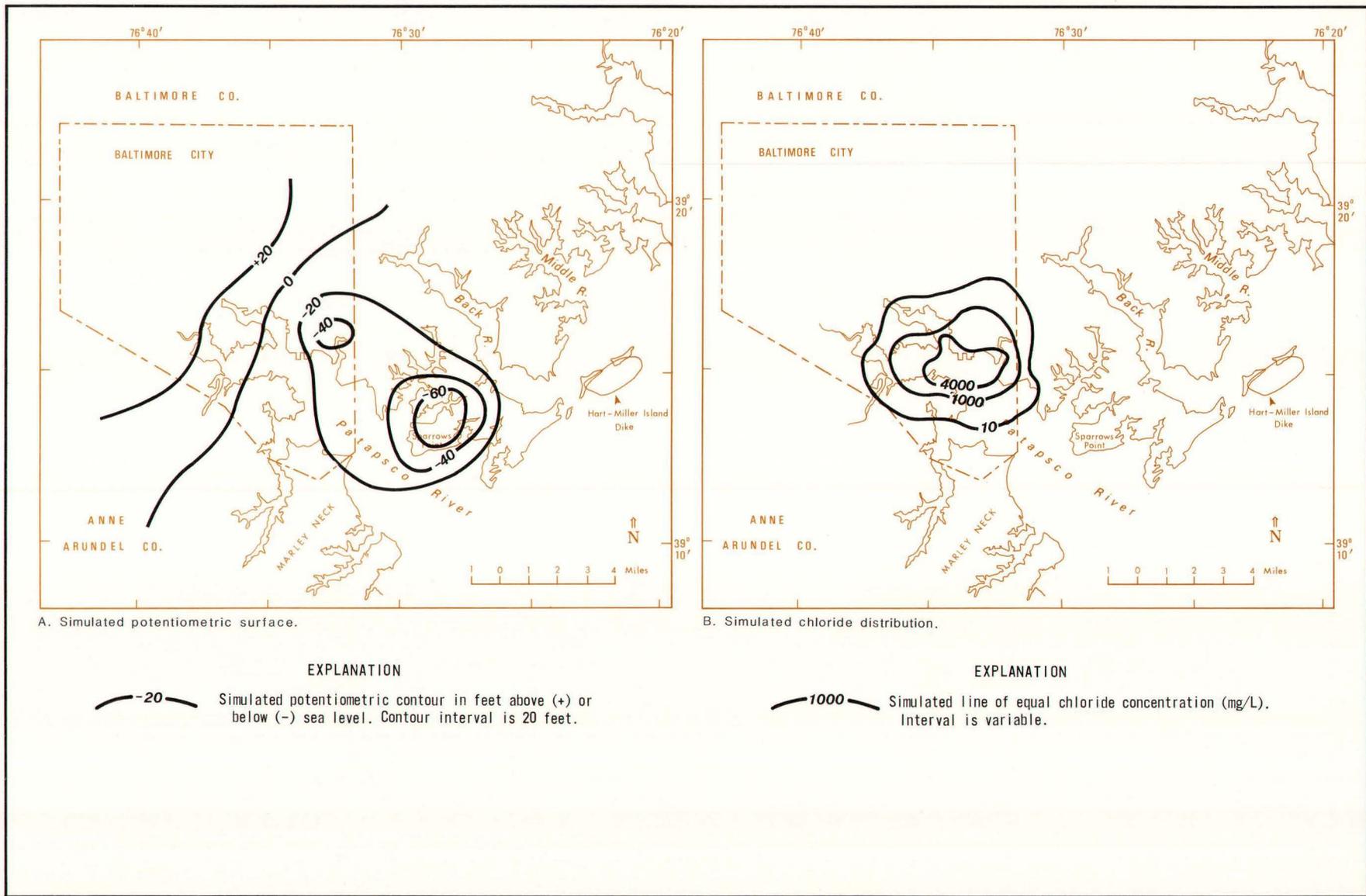
The Anne Arundel County Department of Public Works presently maintains several well fields in the Patuxent aquifer near Glen Burnie. It is likely that pumpage from these well fields will increase considerably in the future as the population increases. One concern that has been raised is the possibility that the chloride contamination plume may be drawn toward the Glen Burnie well fields. Simulation 4 was designed to assess this possibility. However, because the Glen Burnie well field is located near the grid boundary of the digital model (and therefore near a simulated constant-head boundary), the results of this simulation must be regarded as approximate.

In designing simulation 4, it was assumed that 1982 rates of pumpage in Baltimore will continue. Additionally, it was assumed that increased Glen Burnie pumpage would result in a cone of depression reaching approximately 100 ft below sea level. The results of this 50-year simulation are shown in figure 21. The total area of contamination is predicted to increase from 30 to 34.8 mi². There is also a marked shift of the plume toward Glen Burnie. This shift, however, is not large enough or fast enough to constitute a threat to the Glen Burnie well fields in the near future. It is perhaps more significant that chloride concentrations within the plume are predicted to increase in the Fairfield and Curtis Bay districts. Thus, large drawdowns in the Glen Burnie area may contaminate areas between the present (1982) chloride plume and Glen Burnie.

This simulation suggests that the well fields near Glen Burnie may possibly impact the chloride plume. It is unlikely, however, that this effect will result in actual contamination of those well fields in the foreseeable future. It is more likely that, if the plume does shift toward Glen Burnie, increased contamination of the Fairfield and Curtis Bay areas may occur.

Simulation 5

Marley Neck in northern Anne Arundel County is presently undergoing rapid economic development. As a result of this development, increased pumpage from the Patuxent aquifer is possible. The purpose of this simulation is to estimate the effects of increased Marley Neck pumpage on the movement of the chloride plume. In this 50-year simulation, it was assumed that 1982 rates



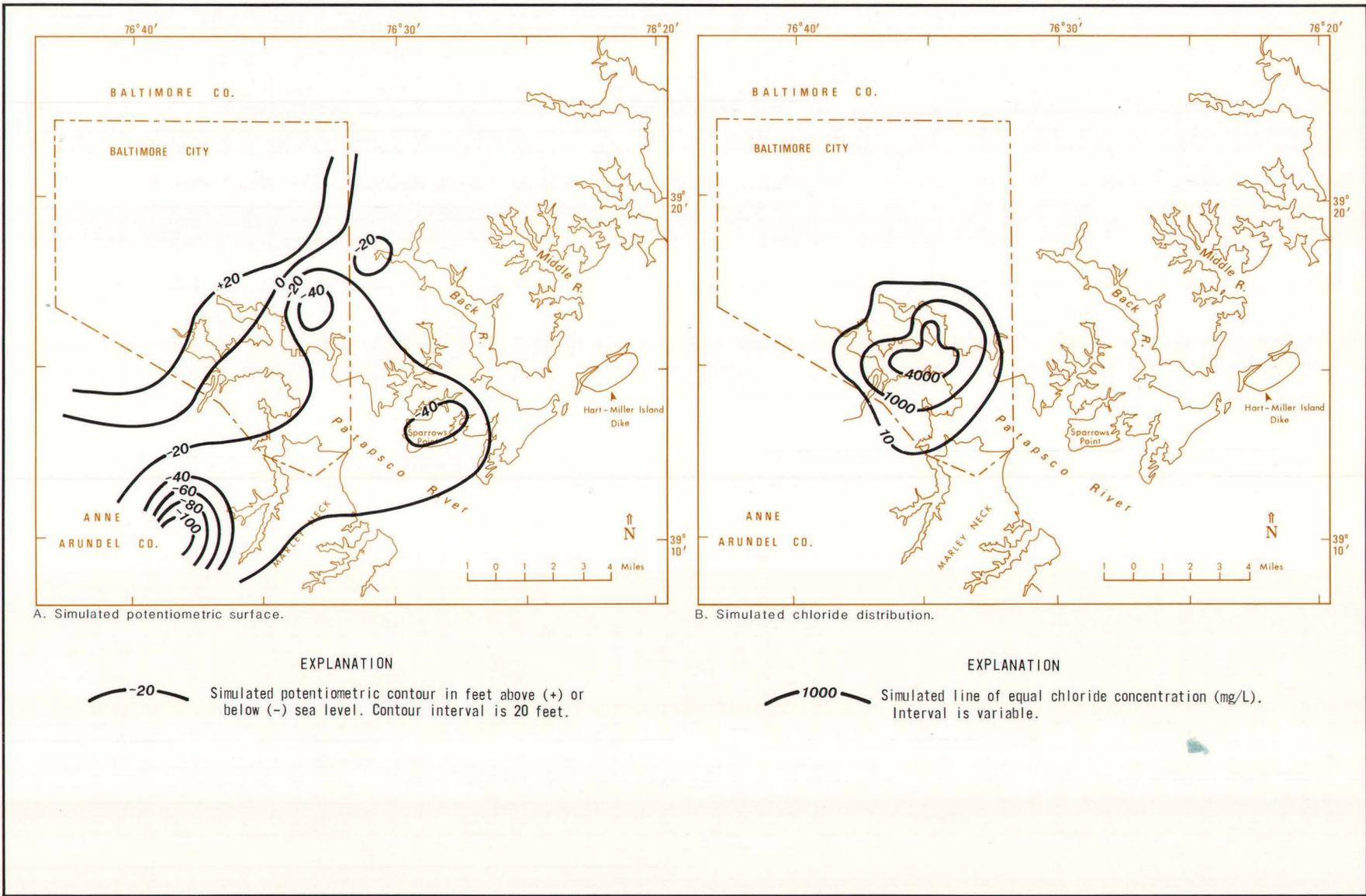
Base map from Bennett, R.R. and Meyer, R.R., 1952

Figure 19.—Simulated potentiometric surface and chloride distribution assuming 9.78-Mgal/d pumpage in the Sparrows Point district and all other pumpage remains at 1982 rates for 50 years.



Base map from Bennett, R.R. and Meyer, R.R., 1952

Figure 20.—Simulated potentiometric surface and chloride distribution assuming all pumpage in Baltimore stops for 50 years.



Base map from Bennett, R.R. and Meyer, R.R., 1952

Figure 21.—Simulated potentiometric surface and chloride distribution assuming 1982 Baltimore pumping rates continue and a 100-ft cone of depression is present at Glen Burnie for 50 years.

of pumpage in the Baltimore area would continue. In addition to this, a 5-Mgal/d well field was specified in Marley Neck (node 9, 13).

The results of simulation 5 are shown in figure 22. A cone of depression extending to about 60 ft below sea level is predicted to develop in response to the pumpage from Marley Neck. In addition, the size of the chloride contamination plume is predicted to increase from 30 to about 35 mi². Furthermore, at the end of the 50-year simulation period, the plume is predicted to have moved within 1 mi of the Marley Neck pumping center.

This simulation suggests that prolonged industrial or municipal pumpage in Marley Neck may induce future chloride contamination. Future planning for water use in that area should carefully consider this possibility.

Simulation 6

The results of simulation 5 suggest that the brackish-water plume could be drawn toward a large pumping center in Marley Neck. One possible strategy to counteract this would be to place a line of fresh-water injection wells between the pumping center and the brackish-water plume. The purpose of simulation 6 is to evaluate this scenario. For this 50-year simulation, it was assumed that 1982 pumping rates would continue and that a 5-Mgal/d well field is located in Marley Neck (as was specified in simulation 5). In addition, a line of four fresh-water injection wells located between the Marley Neck pumping center and the brackish-water plume was also specified. Each of the simulated injection wells recharged the aquifer with chloride-free water at a rate of 1 Mgal/d. The locations of the simulated pumping and injection wells are shown in figure 23.

The results of simulation 6 are shown in figure 23. A cone of depression about 30 ft below sea level is predicted to develop in response to the Marley Neck pumpage. This compares to a cone extending to 60 ft below sea level predicted by simulation 5. The size of the brackish-water plume is predicted to increase from 30 to 31.5 mi². However, this increase is significantly less than that predicted by the nonrecharge scenario of simulation 5. It appears as if artificial fresh-water recharge can, in some cases, significantly slow the rate of chloride movement.

In addition to simulation 6, several other simulations were performed that specified different rates of fresh-water injection. It was found that injecting 10,000

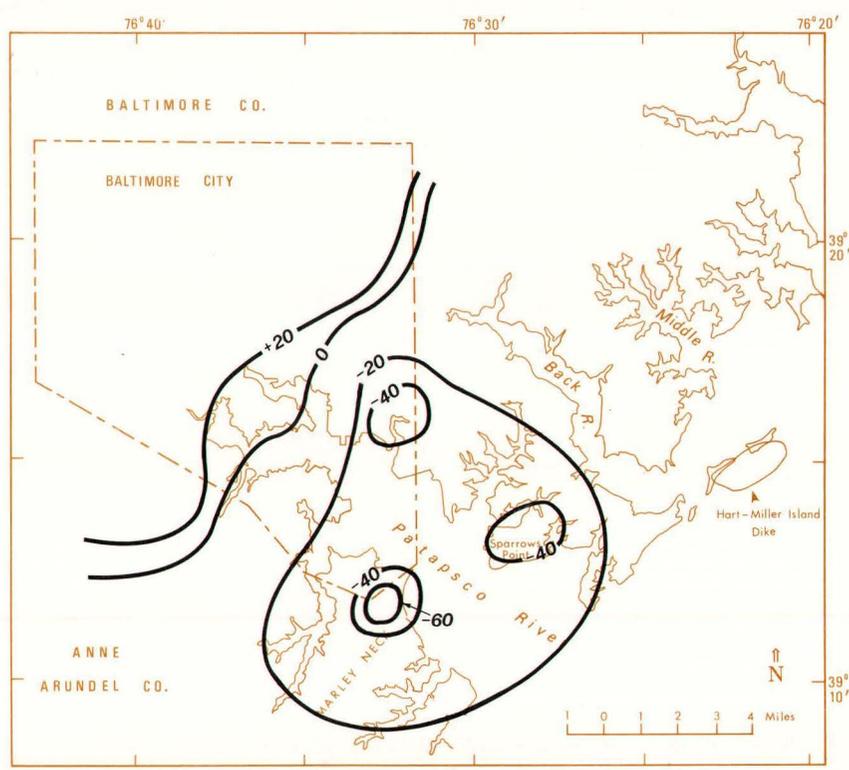
gal/d into each recharge well did not slow down the rate of plume movement relative to the non-injection scenario. This result is important because it demonstrates that the "blocking" effect of recharge is highly dependent on injection rates. If a fresh-water injection program did not recharge the aquifer at sufficiently high rates, then the effect on the plume's movement will be minimal.

Another set of simulations were performed that injected fresh water into the edge of the plume. In this case, part of the brackish-water plume actually moved faster toward the Marley Neck pumping center than in simulation 5. This result is also important because it demonstrates that improper location of injection wells could accelerate, rather than contain, the chloride plume.

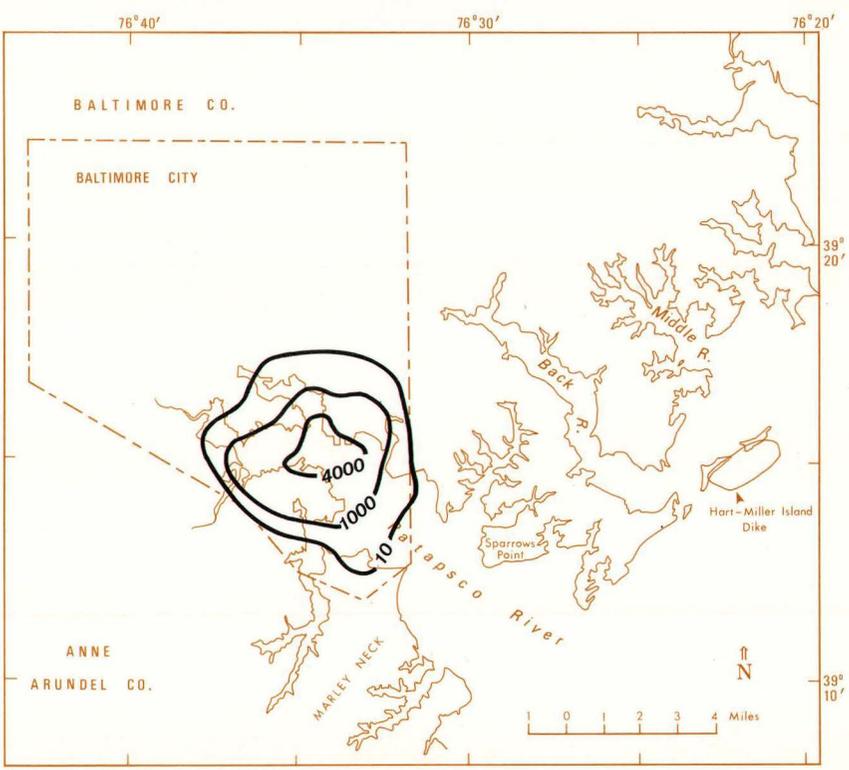
Simulation 6 suggests that a properly located and designed fresh-water injection program can restrict movement of the brackish-water plume. However, many uncertainties about this management alternative remain. For example, injecting water that contains dissolved oxygen into an anoxic aquifer may result in precipitation of colloidal ferric hydroxide. This precipitation could decrease permeability near the injection well screen and eventually lower the rate that water can be injected. Problems of this kind, which cannot be evaluated with the solute-transport model, may limit fresh-water injection programs.

Conclusions

The most important conclusion that can be drawn from the six simulations is that future movement of the chloride plume will probably be very slow. This is in sharp contrast to the plume's movement during the period 1900-45, when it grew and spread very rapidly. It is unlikely that the plume will spread to pumping centers in Sparrows Point or Glen Burnie in the foreseeable future. It is unlikely that simply stopping all pumpage in the Baltimore area will result in any significant improvement in water quality. It is, however, possible that significant pumping stress in the Marley Neck area of Anne Arundel County could cause the plume to migrate toward that pumping center. Placing a line of fresh-water injection wells between pumping centers and the chloride plume may limit plume movement. However, very high rates of fresh-water injection are necessary to achieve this blocking effect. Also, improperly located injection wells may actually accelerate plume movement.

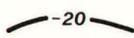


A. Simulated potentiometric surface.



B. Simulated chloride distribution.

EXPLANATION

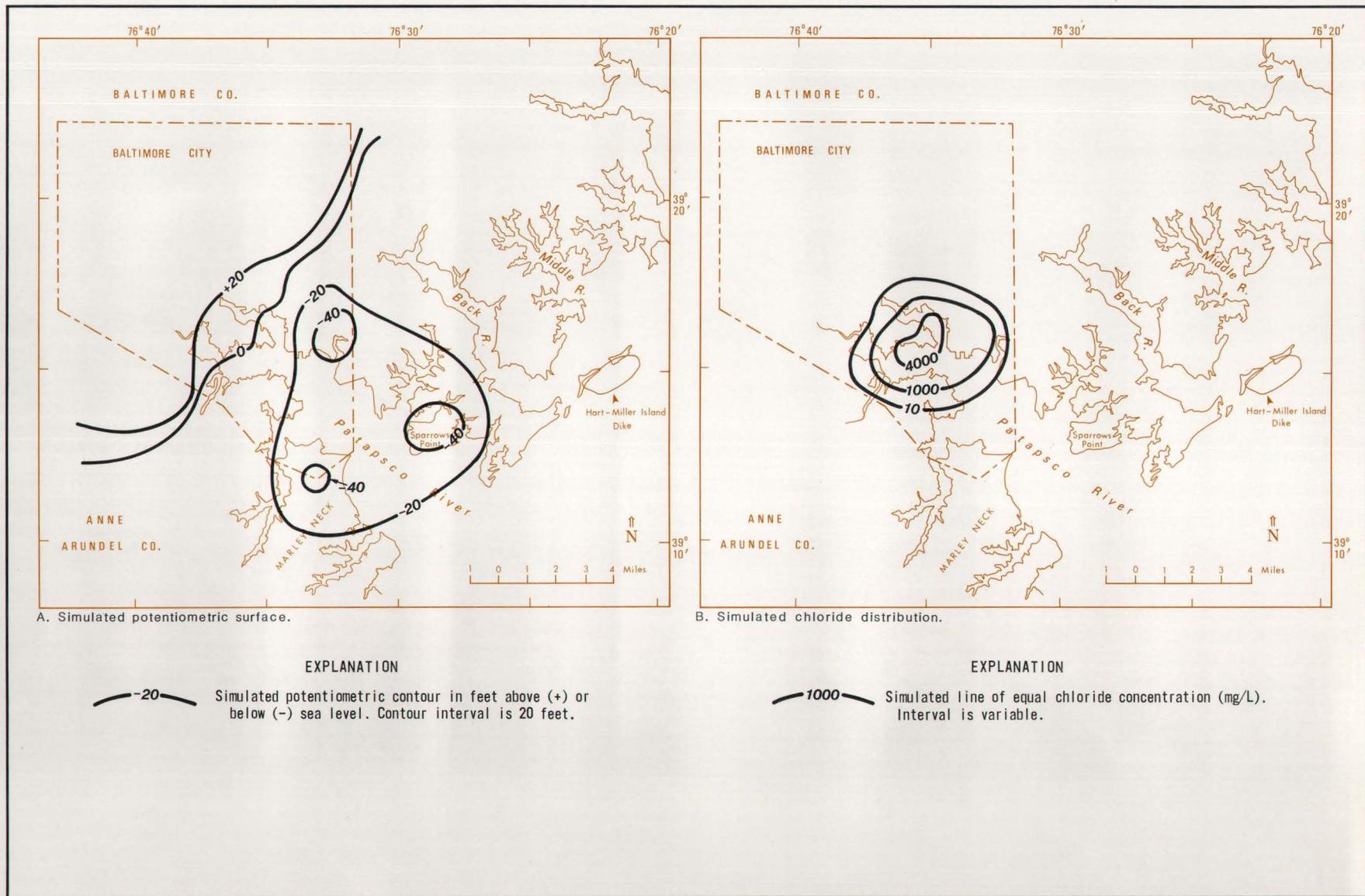
 Simulated potentiometric contour in feet above (+) or below (-) sea level. Contour interval is 20 feet.

EXPLANATION

 Simulated line of equal chloride concentration (mg/L). Interval is variable.

Base map from Bennett, R.R. and Meyer, R.R., 1952

Figure 22.—Simulated potentiometric surface and chloride distribution assuming 5.0-Mgal/d pumpage at Marley Neck and 1982 pumping rates in Baltimore for 50 years.



Base map from Bennett, R.R. and Meyer, R.R., 1952

Figure 23.—Simulated potentiometric surface and chloride distribution assuming a line of fresh-water injection wells are placed between the chloride plume and a 5.0-Mgal/d pumping center at Marley Neck.

GROUND-WATER GEOCHEMISTRY

The chemical quality of ground water has an important bearing on water-supply planning. For an aquifer to be a reliable economic resource, not only must predictable quantities of water be available, but the water must also be of predictable chemical quality. Such predictions require an understanding of the chemical processes that determine water composition in the aquifer. The purpose of this part of the report is to describe the water chemistry of the Patuxent and Patapsco aquifers.

In the Baltimore area, water quality is a particularly important consideration in evaluating ground-water supplies. As has been discussed earlier, brackish-water contamination is a significant problem in the Harbor, Fairfield, and Canton districts (fig. 8). There are, however, several other water-quality problems. For example, in some parts of the Baltimore area, wells produce a water that contains objectionable concentrations of iron or hydrogen sulfide. Other areas are characterized by low-iron water of excellent quality. Why does this areal variability exist, and is it predictable? Another problem deals with ground-water contamination caused by urbanization and/or industrial activity. The Baltimore industrial area has had an active chemical industry for more than 100 years. During this time, chemical spills, petroleum leaks, and improper waste-disposal practices have occurred (Geyer, 1945, p. 11; Bennett and Meyer, 1952, p. 131-132). Have these activities had a measurable impact on water quality? These are some of the questions that will be considered.

As a matter of convenience, the discussion of water chemistry has been divided into several sections. The first section is a general description of water quality in the Patuxent and Patapsco aquifers. This description is designed to:

- (1) Give an overview of the water quality of each aquifer.
- (2) Show the areal variability of water quality in the Baltimore area.
- (3) Show some of the impacts that industrial activity and urbanization have had on water quality.

The second section is an evaluation of the natural chemical evolution of Patuxent aquifer water. The purpose of this section is to:

- (1) Identify the dominant chemical processes that control water composition.

- (2) Show how these processes relate to the observed areal variability of water quality.

This investigation suggests an explanation for the origin and observed spatial distribution of iron hydroxide cementation of the Patuxent aquifer.

WATER QUALITY

Sampling Procedures

Ground-water samples for this study were obtained during the period 1981-83. All samples were taken from wells that had been pumped for a minimum of 1 hour prior to sampling. The pH of water samples was determined in the field with a Sargent-Welch RB 1000 pH meter¹. The pH meter was calibrated with standardized 4.0, 7.0, and 10.0 pH-buffer solutions in the field prior to each determination. Alkalinity was determined in the field by titrating a 50 ml aliquot of sample to pH 4.5 with 0.01639 normal H₂SO₄. Concentrations of dissolved oxygen, hydrogen sulfide, and chloride also were determined in the field. Dissolved oxygen concentrations were measured with a Hach model OX-DT field kit. Special procedures were used to obtain samples for dissolved oxygen determinations. A small-diameter hose was attached to the discharge pipe of the well. This hose was placed inside a standard BOD bottle and filled with water. Once filled, the BOD bottle and hose were immersed in a bucket of water so that it was isolated from the atmosphere. The hose was then allowed to purge the BOD bottle for a period of not less than 5 minutes. The BOD bottle was capped while still immersed, and then removed for analysis. The Hach-kit analysis is a modification of a standard Winkler titration for dissolved oxygen.

Additional samples were preserved in the field according to methods described in the National Handbook of Recommended Methods for Water Data Acquisition (U.S. Geological Survey, 1977). Samples to be analyzed for concentrations of dissolved iron were filtered in the field through a 0.1 micron filter and then acidified by adding 1 milliliter of concentrated nitric acid. Samples were sent to the U.S. Geological Survey Central Laboratory, Doraville, Ga., for analysis of major ions, metals and organic substances.

¹Use of trade names in this report is for identification purposes and does not constitute endorsement.

Patuxent Aquifer

The results of chemical analyses of Patuxent aquifer water collected during the period 1981-83 are listed in tables 6a-c. Table 6a lists the major dissolved constituents and nutrients, table 6b lists minor and trace dissolved constituents, and table 6c lists dissolved

organic compounds. The locations of wells included in tables 6a-c are shown on plate 1.

The data in tables 6a-c show that the water quality of the Patuxent aquifer is extremely variable. Chloride concentrations range from 1.1 to 5,000 milligrams per liter (mg/L), pH ranges from 4.4 to 6.5, and iron concentrations range from less than 0.003 to 53 mg/L. In

Table 6a.—Chemical-quality analyses of ground water from selected wells in the Patuxent aquifer—Major dissolved constituents and nutrients

USGS Well No.	Geologic unit	Date of sample	Silica, dissolved (mg/L as SiO ₂)	Oxygen, dissolved (mg/L)	Iron, dissolved (µg/l as Fe)	Calcium dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Alkalinity, field (mg/L as CaCO ₃)	Sulfate dissolved (mg/L as SO ₄)
Anne Arundel County											
Ad 76	217PTXN	11-18-81	9.7	0.5	30	0.5	0.3	1.0	0.5	3.0	7.5
Ad 98	217PTXN	12-09-81	--	<.2	--	--	--	--	--	18.0	--
Ad 99	217PTXN	12-09-81	9.5	<.2	5100	1.3	.8	1.5	.9	8.0	12
Ae 36	217PTXN	04-07-82	9.0	<.2	3600	1.1	.6	1.5	.8	10	8.1
Bd 66	217PTXN	05-11-82	8.9	<.2	460	.4	.4	.8	.6	1.0	5.0
Bd 97	217PTXN	05-12-82	8.6	.3	170	.4	.3	.7	.4	<1.0	6.0
Bd 98	217PTXN	05-10-82	9.0	<.2	1200	.5	.3	1.1	.6	2.0	7.0
Baltimore County											
Eg 154	217PTXN	08-24-82	6.7	11.1	<3	3.0	1.5	3.8	1.3	5.0	1.0
Fe 51	217PTXN	04-28-82	8.3	5.8	27	5.4	1.9	8.2	1.0	7.0	2.0
Fe 59	217PTXN	04-21-82	8.1	8.6	6	1.2	.7	2.4	.5	7.0	2.0
Fe 64	217PTXN	04-21-82	12	2.0	3500	32	19	33	2.3	8.0	130
Fe 66	217PTXN	02-21-82	11	.5	9700	32	21	50	3.6	11	110
Fe 69	217PTXN	07-22-82	7.3	7.7	220	.7	.4	2.1	.3	8.0	3.0
Ff 85	217PTXN	04-19-82	8.6	1.1	180	1.7	1.3	6.2	1.1	7.0	9.0
Fg 69	217PTXN	04-19-82	8.9	<.2	5300	2.8	2.2	7.3	2.0	21	11
Gc 25	217PTXN	06-11-81	8.2	--	230	.8	.3	5.8	.8	7.0	5.7
Gf 210	217PTXN	12-02-81	9.7	<.2	9100	5.0	2.3	3.8	2.3	35	11
Gf 212	217PTXN	11-30-81	--	<.2	--	--	--	--	--	28.0	--
Gf 220	217PTXN	11-30-81	11	<.2	8400	4.7	2.7	6.1	2.2	32.0	11
Gg 13	217PTXN	04-18-83	8.7	<.2	9800	1.4	1.5	11	1.8	41.1	9.9
Baltimore City											
1N5E 4	217PTXN	12-07-81	6.3	1.1	120	63	22	74	14	140	180
1N3E 9	217PTXN	05-03-82	8.6	2.1	34	27	13	39	2.9	6.0	97
1N3E11	217PTXN	05-03-82	8.1	1.2	<9	30	15	48	2.8	7.0	130
1S3E45	217PTXN	12-04-81	--	1.1	--	--	--	--	--	28.0	--
1S3E46	217PTXN	12-04-81	7.4	1.4	12	23	12	80	3.4	5.0	37
1S3E47	217PTXN	12-04-81	--	2.9	--	--	--	--	--	--	--
2S5E 4	217PTXN	12-07-81	--	.4	--	--	--	--	--	59.0	--
3S2E 5	217PTXN	11-23-82	11	2.8	580	86	55	550	5.9	87	85
3S3E36	217PTXN	03-20-81	4.1	--	610	140	270	2700	65	350	240
	217PTXN	04-06-82	5.7	.8	790	150	240	2000	61	349	230
3S3E37	217PTXN	03-13-81	5.4	--	4800	110	340	3000	85	300	230
3S3E38	217PTXN	03-26-81	39	--	49000	130	170	1600	25	--	120
	217PTXN	04-06-82	33	.3	52000	140	160	1600	21	--	110
3S3E39	217PTXN	03-20-81	4.7	--	53000	95	190	2000	47	7.0	230
3S4E15	217PTXN	10-01-81	14	1.2	77	74	21	170	5.8	28	150
3S5E35	217PTXN	04-16-82	11	3.4	1600	29	25	220	3.6	2.0	74
3S5E39	217PTXN	04-16-82	7.8	6.8	12	1.8	1.1	6.1	.4	4.0	3.0
3S5E40	217PTXN	04-16-82	--	6.8	--	--	--	--	--	3.0	--
3S5E41	217PTXN	04-16-82	11	4.4	1500	29	25	210	3.6	3.0	74
3S5E42	217PTXN	04-19-82	9.4	4.5	1000	19	17	140	2.5	3.0	33
	217PTXN	04-23-82	6.6	1.5	50	85	83	760	13	20	130
3S5E43	217PTXN	04-16-82	10	5.2	41	13	7.3	36	1.5	3.0	36
3S5E44	217PTXN	10-04-82	8.4	9.4	3	3.4	1.4	6.5	.8	2.0	2.0
5S2E20	217PTXN	04-23-82	7.4	7.7	130	7.9	5.1	37	1.3	2.0	19
5S2E24	217PTXN	12-02-82	7.2	5.3	550	2.6	.6	3.4	.9	13	2.0

view of this extreme variability, it is convenient to subdivide the aquifer into zones that have similar water compositions. For the purposes of this report, three water-quality zones are recognized in the Patuxent aquifer.

Zone 1.—This zone corresponds to the plume of brackish-water contamination. This zone is recharged in

part by brackish water from the Patapsco River and is characterized by high-chloride concentrations (50 to 5,000 mg/L). In addition to the high-chloride concentrations, zone 1 water is characterized by a calcium/chloride (Ca/Cl) ratio of less than 0.1. This reflects the low Ca/Cl ratio of brackish water in the Patapsco River estuary (Bricker and others, 1977).

**Table 6a.—Chemical-quality analyses of ground water from selected wells in the Patuxent aquifer—
Major dissolved constituents and nutrients—Continued**

Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Nitrogen, nitrate dissolved (mg/L as N)	Nitrogen, ammonia & organics total (mg/L as N)	Nitrogen, total (mg/L as N)	Hydrogen sulfide dissolved (mg/L as H ₂ S)	Solids, residue at 180°C dissolved (mg/L)	Solids, sum of constituents, dissolved (mg/L)	Hardness as CaCO ₃ (mg/L)	Specific conductance (µmhos 25°C)	pH (units)	Temperature (°C)	USGS Well No.
1.4	<0.1	--	--	--	--	22	23	3	35	4.3	15.0	Ad 76
5.3	--	--	--	--	--	--	--	--	42	8.2	12.5	Ad 98
2.5	<.1	--	.13	.19	0.3	52	37	7	55	6.0	11.0	Ad 99
3.4	<.1	--	--	--	0.03	24	32	5	39	5.8	15.0	Ae 36
--	--	--	--	--	--	--	--	--	52	4.9	13.0	Bd 64
1.1	<.1	--	--	--	--	19	18	3	32	4.6	16.0	Bd 66
1.1	<.1	--	--	--	--	20	23	3	33	4.9	14.5	Bd 98
7.8	<.1	--	--	--	--	--	28	14	62	5.3	16.0	Eg 154
14	--	--	2.80	7.7	--	86	46	21	93	5.4	13.0	Fe 51
3.0	<.1	--	.29	.67	--	22	22	6	300	5.7	14.0	Fe 59
61	.2	--	.53	3.1	--	355	304	160	550	5.2	14.0	Fe 64
110	.3	--	.93	2.2	--	412	380	170	740	5.2	15.0	Fe 66
2.2	<.1	--	--	--	0.03	28	22	4	26	5.5	15.0	Fe 69
7.1	<.1	--	.41	--	--	37	40	10	62	5.4	16.0	Ff 85
6.9	<.1	--	.26	--	--	50	55	16	98	6.2	16.5	Fg 69
6.7	.2	--	--	--	--	31	33	3	52	5.0	13.5	Gc 25
5.7	.1	--	--	--	0.15	26	63	22	132	6.4	14.5	Gf 210
6.7	--	--	--	--	--	--	--	--	112	6.2	18.0	Gf 212
5.9	.1	--	--	--	0.03	53	68	23	122	6.4	18.0	Gf 220
2.7	.2	--	--	--	0.01	--	80	10	107	6.5	17.5	Gg 13
94	<.1	--	--	--	--	666	540	250	835	6.1	14.5	IN5E 4
66	.1	--	--	--	--	311	259	120	52	5.0	16.0	IN3E 9
73	.1	--	--	--	--	345	313	140	56	4.9	15.5	IN3E11
95.2	--	--	--	--	--	--	--	--	560	5.4	17.0	1S3E45
94	.2	--	--	--	--	463	260	110	840	4.8	14.5	1S3E46
--	--	--	--	--	--	--	--	--	335	4.7	14.5	1S3E47
6.4	--	--	--	--	--	--	--	--	143	7.5	14.0	2S5E 4
1200	<.1	--	--	--	--	2080	2050	440	1060	5.2	14.5	3S2E 5
4700	.3	--	--	--	--	7990	8340	1500	10200	6.4	15.0	3S3E36
4400	.1	--	--	--	--	7510	7310	1400	13640	6.3	15.0	
6000	.3	--	--	--	--	10300	9960	1700	14300	6.6	15.0	3S3E37
3500	.5	--	--	--	--	6180	5670	1000	8400	4.3	16.0	3S3E38
3600	.6	--	4.10	4.7	--	5780	5750	1000	9072	3.6	14.5	
3800	.3	--	--	--	--	6160	6440	1000	7680	5.8	15.0	3S3E39
290	.4	.33	--	--	--	763	745	270	1200	5.7	15.5	3S4E15
360	.4	--	.65	3.1	--	705	731	180	1450	4.6	14.0	3S5E35
8.5	<.1	--	.35	1.3	--	36	31	9	52	5.1	14.0	3S5E39
67.1	--	--	--	--	--	--	--	--	1750	4.9	14.0	3S5E40
400	.4	--	.77	3.2	--	846	763	180	1440	4.8	15.0	3S5E41
260	.2	--	.77	2.5	--	530	447	120	1180	4.9	15.0	3S5E42
1600	.5	--	2.70	--	--	3010	2700	550	5300	5.2	15.0	
53	.2	--	.33	5.0	--	174	162	63	2050	4.9	14.0	3S5E43
12	<.1	--	--	--	--	70	36	14	86	4.6	14.0	3S5E44
81	<.1	--	.29	2.4	--	172	161	41	330	4.8	13.5	5S2E20
2.7	<.1	--	--	--	--	30	28	9	46	6.0	15.0	5S2E24

Zone 2.—This zone is characterized by urbanization-related chemical contamination. Chloride concentrations range from 20 to 100 mg/L and the Ca/Cl ratio is greater than 0.1. This reflects the relatively large Ca/Cl ratio characteristic of dissolved road salts and other urbanization-related runoff. Water in this zone contains high concentrations of total organic carbon (TOC) and may contain measurable concentrations of industrial organic chemicals. Trichloroethelene, toluene, and benzene are the most commonly observed chemicals of this type that occur in zone 2.

Zone 3.—Water in zone 3 does not appear to have artificial contamination. This zone is distinguished primarily by low-chloride concentrations (1 to 5 mg/L Cl⁻). The pH of zone 3 water is low and ranges from 4.5 to 6.5. Zone 3 water quality is controlled by natural chemical processes.

The areal extents of zones 1, 2, and 3 are shown in figure 24. Also included in figure 24 are representative analyses of each zone. Zone 1 is limited to the area adjoining the Patapsco River estuary. There is some

Table 6b. — Chemical-quality analyses of ground water from selected wells in the Patuxent aquifer— Minor and trace dissolved constituents

USGS Well No.	Geologic unit	Date of sample	Chromium dissolved (µg/L as Cr)	Fluoride dissolved (mg/L as F)	Carbon, organic total (mg/L as C)	Arsenic dissolved (µg/L as As)	Barium, dissolved (µg/L as Ba)	Beryllium, dissolved (µg/L as Be)	Boron, dissolved (µg/L as B)	Cadmium dissolved (µg/L as Cd)
Anne Arundel County										
Ad 76	217PTXN	11-18-81	5	<0.1	<0.1	1	15	<1	<10	1
Ad 99	217PTXN	12-09-81	<1	<.1	<.1	0	20	<1	<10	2
Ae 36	217PTXN	04-07-82	4	<.1	.4	1	18	<1	<20	<1
Bd 66	217PTXN	05-11-82	<1	<.1	.1	<1	11	<1	<20	<1
Bd 97	217PTXN	05-12-82	<1	<.1	1.4	<1	11	<1	<20	<1
Bd 98	217PTXN	05-10-82	<1	<.1	.4	<1	13	<1	<20	<1
Baltimore County										
Eg 154	217PTXN	08-24-82	--	<.1	.3	--	30	1	--	1
Fc 51	217PTXN	04-28-82	2	--	.6	1	41	<1	<20	<1
Fe 59	217PTXN	04-21-82	<1	<.1	.1	1	16	<1	<20	<1
Fe 64	217PTXN	04-21-82	3	.2	1.1	1	100	2	140	1
Fe 66	217PTXN	04-21-82	1	.3	.8	1	130	2	220	<1
Fe 69	217PTXN	07-22-82	<1	<.1	.1	<1	14	<1	<10	<1
Ff 85	217PTXN	04-19-82	<1	<.1	<.1	1	21	<1	<20	<3
Fg 69	217PTXN	04-19-82	<1	<.1	.2	1	31	1	<20	<3
Gc 25	217PTXN	06-11-81	--	.2	.3	--	--	--	--	--
Gf 210	217PTXN	12-02-81	5	.1	<.1	0	26	<1	<10	<1
Gf 220	217PTXN	11-30-81	3	.1	<.1	0	27	1	<10	1
Gg 13	217PTXN	04-18-83	6	.2	.9	1	100	10	50	2
Baltimore City										
IN5E 4	217PTXN	12-07-81	<1	<.1	3.3	0	34	<1	260	2
IN3E 9	217PTXN	05-03-82	<1	.1	1.3	1	76	<1	<10	<1
IN3E11	217PTXN	05-03-82	<1	.1	1.6	1	60	<1	70	<1
1S3E46	217PTXN	12-04-81	1	.2	1.0	0	130	<1	60	3
3S2E 5	217PTXN	11-23-82	4	<.1	.4	1	400	<10	10	1
3S3E36	217PTXN	03-20-81	0	.3	4.6	0	100	20	270	0
	217PTXN	04-06-82	2	.1	1.2	1	100	<10	230	1
3S3E37	217PTXN	03-13-81	0	.3	--	2	100	30	830	0
3S3E38	217PTXN	03-26-81	0	.5	.9	1	300	30	120	0
	217PTXN	04-20-82	<1	.6	1.6	1	300	10	40	3
3S3E39	217PTXN	03-20-81	0	.3	1.9	0	100	30	410	0
3S4E15	217PTXN	10-01-81	<1	.4	4.1	2	80	2	60	5
3S5E35	217PTXN	04-16-82	<1	.4	1.6	1	85	4	60	4
3S5E39	217PTXN	04-16-82	<1	<.1	.4	1	22	1	<20	<3
3S5E41	217PTXN	04-16-82	<1	.4	2.1	1	85	4	70	<3
3S5E42	217PTXN	04-19-82	<1	.2	.9	1	58	<3	30	<3
	217PTXN	04-23-82	<1	.5	1.0	1	100	<10	70	11
3S5E43	217PTXN	04-16-82	<1	.2	.8	1	49	3	960	<3
3S5E44	217PTXN	10-04-82	<1	<.1	.8	2	26	1	50	1
5S2E20	217PTXN	04-23-82	1	<.1	.2	1	33	<3	<20	<1
5S2E24	217PTXN	12-02-82	1	<.1	.2	<1	15	<1	<10	2

evidence that brackish-water intrusion also is occurring in the Back River district from the Back River estuary. The area of contamination is very small in areal extent and appears to be related to the Back River district pumping center (table 3). This area is labeled as zone 1a in figure 24. Zone 3 in figure 24 has been subdivided into zone 3a, in which ground water contains measurable concentrations of dissolved oxygen (DO), and zone 3b, in which water does not contain measurable DO. Water in zone 3b has much higher dissolved iron concentrations than zone 3a. Also, water in zone 3b commonly

contains measurable concentrations of dissolved hydrogen sulfide.

Contamination of ground-water supplies by industrial organic chemicals presently is a topic of much public concern. Table 6c lists analyses of 21 water samples from 19 wells tapping the Patuxent aquifer. These samples were collected specifically to determine organic chemical concentrations. Six of the 21 samples had measurable concentrations of organic chemicals. The chemicals most in evidence were trichloroethylene, benzene, toluene, and ethyl benzene. None of these

**Table 6b.—Chemical-quality analyses of ground water from selected wells in the Patuxent aquifer—
Minor and trace dissolved constituents—Continued**

Cobalt, dis- solved (µg/L as Co)	Copper, dis- solved (µg/L as Cu)	Lead, dis- solved (µg/L as Pb)	Manga- nese, dis- solved (µg/L as Mn)	Molyb- denum, dis- solved (µg/L as Mo)	Nickel, dis- solved (µg/L as Ni)	Silver, dis- solved (µg/L as Ag)	Stron- tium, dis- solved (µg/L as Sr)	Zinc dis- solved (µg/L as Zn)	Anti- mony, dis- solved (µg/L as Sb)	Lithium dis- solved (µg/L as Li)	USGS Well No.
8	19	3	23	<1	12	<1	4	54	<1	8	Ad 76
2	<1	<1	76	1	6	<1	11	13	1	13	Ad 99
3	<1	4	75	<1	2	<1	9	9	<1	12	Ae 36
5	5	4	19	<1	9	<1	3	28	<1	5	Bd 66
7	13	8	16	<1	15	<1	2	22	<1	5	Bd 97
4	7	3	35	<1	7	<1	4	16	<1	6	Bd 98
3	4	22	9	8	--	--	18	14	--	<4	Eg 154
8	560	6	53	<1	15	<1	23	50	<1	5	Fe 51
2	15	<1	11	<1	8	<1	7	20	<1	7	Fe 59
250	33	1	3900	<1	140	<1	160	1300	<1	27	Fe 64
390	26	3	4900	<1	230	<1	190	19000	<1	41	Fe 66
6	460	5	37	<1	11	<1	4	23	<1	5	Fe 69
5	2	1	89	<1	12	<1	17	<3	<1	<10	Ff 85
<1	2	1	140	<1	3	<1	35	<3	<1	<10	Fg 69
--	--	--	10	--	--	--	--	--	--	--	Gc 25
1	5	2	210	2	1	<1	65	5	<1	9	Gf 210
<1	1	4	210	2	1	<1	67	4	<1	12	Gf 220
3	3	22	230	<1	3	<1	40	10	<1	10	Gg 13
12	15	<1	1300	1	11	<1	340	36	<1	<4	IN5E 4
33	22	2	570	<1	39	<1	140	280	<1	5	IN3E 9
40	24	3	760	<1	45	<1	160	470	<1	5	IN3E11
120	70	<1	470	1	130	<1	92	190	<1	11	1S3E46
68	12	2	230	<1	270	<1	420	580	1	10	3S2E 5
79	10	0	2900	0	14	0	1100	30	0	10	3S3E36
36	<1	10	3200	<1	14	<1	3300	30	<1	<10	
49	130	1	3600	0	14	0	1600	40	0	10	3S3E37
470	70	100	16000	0	300	2	1000	640	0	30	3S3E38
400	91	73	18000	<1	430	<1	3700	880	<1	40	
110	280	0	9000	0	23	0	1100	60	0	10	3S3E39
82	59	3	880	<1	610	1	360	240	2	12	3S4E15
170	1800	2	1600	<1	360	<1	180	760	<1	12	3S5E35
19	3	1	--	<1	21	<1	8	<3	<1	16	3S5E39
160	1900	2	1700	<1	440	<1	180	750	<1	<10	3S5E41
95	1100	2	980	<1	120	<1	110	<3	<1	<10	3S5E42
270	3100	2	3300	<1	720	<1	490	490	<1	10	
43	1100	2	350	<1	330	<1	61	<3	<1	<10	3S5E43
8	<1	2	98	<1	10	<1	22	270	2	10	3S5E46
12	33	2	85	<1	15	<1	41	33	<1	<12	5S2E20
4	7	1	53	<1	4	<1	13	280	2	<4	5S2E24

chemicals is known to be present naturally in ground water and their presence strongly suggests artificial contamination of the aquifer. It is significant that the contamination appears to be confined to the Canton and Highlandtown districts. These areas have had intense industrial activity for many years. The observed contamination is almost certainly a result of that industrial activity. Equally significant is the lack of organic chemical contamination in areas adjacent to the Canton and Highlandtown districts. This suggests that the chemicals have not moved appreciably from the area of initial contamination. The data presently available are not sufficient to evaluate the hydrologic or chemical factors for the observed lack of mobility. Similarly, the data also are insufficient to reliably identify the sources of contamination.

Another topic of public concern is ground-water contamination by trace metals. Wells 3S3E-36 to 3S3E-40 in the Canton district produce water containing relatively high concentrations (2.9 to 18.0 mg/L) of manganese (table 6b). This water also contains higher concentrations of zinc (0.5 – 9.0 mg/L) and iron (0.6 to 39.0 mg/L; table 6a) than commonly found in Patuxent

water. The area of Canton where these wells are located also is highly contaminated by brackish-water intrusion. It may be significant that this water contains relatively low concentrations of dissolved oxygen (0.3 to 0.8 mg/L; table 6a). It appears that brackish water, which has been in contact with organic-rich, channel-fill sediments, is much more reducing than formational water in this area. The reducing brackish water may have mobilized iron, manganese, and other metals from the channel-fill sediments. This in turn may explain the observed trace metal concentrations.

Some wells in the Dundalk district also have relatively high concentrations of trace metals. Water produced from wells 3S3E-35 to 3S5E-44 (tables 6a and 6b) have iron, manganese, and zinc concentrations similar to those found in the Canton district. Brackish-water intrusion has contaminated water in the Dundalk area and it is possible that trace metals have been mobilized from channel-fill sediments by this relatively reducing water. Some of these wells also contain relatively high concentrations of copper (1.1 to 3.1 mg/L). It is significant that in this high-copper water, copper concentrations are directly proportional to sulfate con-

**Table 6c. — Chemical-quality analyses of ground water from selected wells in the Patuxent aquifer—
Dissolved organic compounds**

USGS Well No.	Date of sample	Geologic unit	1,2-Di-chloro-ethane total (µg/L)	Bromo-form total (µg/L)	Chloro-di-bromo-methane total (µg/L)	Chloro-oform total (µg/L)	Toulene total (µg/L)	Benzene total (µg/L)	Chloro-benzene total (µg/L)	Chloro-ethane total (µg/L)	Ethyl-benzene total (µg/L)	
Anne Arundel County												
Ad 76	07-15-82	217PTXN	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	
Ad 99	07-14-82	217PTXN	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	
Baltimore County												
Fe 59	07-15-82	217PTXN	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	
Ff 85	07-13-82	217PTXN	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	
Fg 69	07-13-82	217PTXN	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	
Gf 210	07-14-82	217PTXN	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	
Baltimore City												
IN3E11	07-16-82	217PTXN	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	
1S3E46	07-16-82	217PTXN	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	
1S3E47	07-16-82	217PTXN	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	
3S2E 5	11-30-82	217PTXN	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	
3S5E35	07-13-82	217PTXN	<1.0	<1.0	<1.0	<1.0	14	220	<1.0	<1.0	<1.0	
3S5E39	07-13-82	217PTXN	<1.0	<1.0	<1.0	<1.0	<1.0	43	<1.0	<1.0	<1.0	
	10-04-82	217PTXN	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	
3S5E40	10-04-82	217PTXN	<1.0	<1.0	<1.0	<1.0	1.0	61	<1.0	<1.0	2.0	
3S5E41	07-13-82	217PTXN	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	
3S5E42	07-13-82	217PTXN	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	
	10-04-82	217PTXN	<1.0	5.0	<1.0	<1.0	<1.0	5.0	<1.0	<1.0	<1.0	
3S5E43	07-13-82	217PTXN	4.0	<1.0	<1.0	<1.0	18	230	<1.0	<1.0	15	
3S5E44	10-04-82	217PTXN	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	
5S2E20	07-14-82	217PTXN	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	
5S2E24	12-02-82	217PTXN	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	

centrations. This suggests that the source of copper is related to a source of sulfate. Throughout much of the 19th century and into the early 20th century, several Baltimore industries were active in smelting copper sulfide ores (Darton, 1896, p. 138). According to Geyer (1945, p. 11) the slag from these operations was dumped on vacant land in the Canton district. Geyer (1945, p. 11) documents that leachate from this slag was highly acid in character (pH 2-3). Bennett and Meyer (1952, p. 158) show that this leachate had entered the Patuxent aquifer and was moving toward the Dundalk district. It is probable that this copper-slag leachate is the source of the presently observed copper contamination in Dundalk. If this is the case, the copper-slag leachate has moved approximately 1/2 to 1 mi since entering the aquifer. It is significant that this high-copper water does not now exhibit low pH. This may be due to the pH-buffering properties of clay minerals in the Patuxent aquifer. These pH-buffering properties will be discussed in the section on Chemical Evolution of Ground Water.

Patapsco Aquifer

The results of chemical analyses of Patapsco aquifer water collected during the period 1981-83 are presented in tables 7a-c. Table 7a lists the major dissolved constituents and nutrients, table 7b lists minor and trace dissolved species, and table 7c lists dissolved organic compounds. The locations of wells included in table 7 are shown on plate 1.

The Patapsco aquifer is not presently (1982) being tapped as a major source of ground water in Baltimore City. The closest major center of pumpage from the Patapsco aquifer is in Glen Burnie. Because of the lack of aquifer use, it was difficult to locate wells suitable for water-quality sampling. Two of the water samples were from wells drilled and completed as part of this study (wells 5S2E-25 and 3S5E-46). It is not presently possible to define Patapsco aquifer water quality as precisely as might be desired because of this paucity of water-sampling sites.

Table 6c.—Chemical-quality analyses of ground water from selected wells in the Patuxent aquifer—Dissolved organic compounds—Continued

Methyl- bromide total (µg/L)	Methyl- chloro- ride total (µg/L)	Tetra- chloro- ethyl- ene total (µg/L)	Tri- chloro- fluoro- methane total (µg/L)	1,1-Di- chloro- ethane total (µg/L)	1,1-Di- chloro- ethyl- ene total (µg/L)	1,1,1- chloro- ethane total (µg/L)	1,1,2- Tri- chloro- ethane total (µg/L)	1,1,2,2 Tetra- chloro- ethane total (µg/L)	1,2-Di- chloro- propane total (µg/L)	Chloro- ethyl- ene total (µg/L)	1,3-Di- chloro- propane total (µg/L)	USGS Well No.
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	Ad 76
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	Ad 99
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	Fe 59
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	Ff 85
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	Fg 69
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	Gf 210
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	IN3E11
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	1S3E46
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	1S3E47
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	3S2E 5
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	7.0	<1.0	<1.0	<1.0	<1.0	<1.0	3S5E35
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	3S5E39
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	3S5E40
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	3S5E41
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	3S5E42
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	3S5E43
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	3S5E44
<1.0	<1.0	2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	5S2E20
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	5S2E24

The Patapsco aquifer near Baltimore functions primarily as a water-table aquifer. Because of this, the Patapsco is susceptible to contamination from industrial and urban waste. The relative ease with which industrial pollutants may reach the Patapsco is reflected in its water quality.

The data in table 7 indicate that the Patapsco aquifer is characterized by low-pH, low-alkalinity water. Dissolved iron concentrations tend to be variable and range from 0.01 to 3.3 mg/L. Because Patapsco aquifer water commonly contains measurable dissolved oxygen, dissolved iron concentrations tend to be rather low. Samples of Patapsco aquifer water that did not contain measurable dissolved oxygen generally contained low concentrations of hydrogen sulfide.

Many of the water analyses from the Patapsco aquifer in table 7 show evidence of urbanization-related contamination. For example, in Anne Arundel County, wells Ad-41, Ad-67, and Ad-74 have chloride concentrations greater than 10 mg/L. Because the Ca/Cl ratio is greater than 0.1, it is probable that road salts have been dissolved by rainwater, moved through the unsaturated zone, and finally recharged the aquifer. The most im-

portant evidence of urbanization-related contamination, however, is the presence of organic compounds such as benzene, trichloroethelene, and toluene. Of the five Patapsco aquifer wells sampled for organic compounds, four showed measurable concentrations of these chemicals. Because such chemicals are not present naturally in ground-water systems, this almost certainly reflects contamination due to human-related activity.

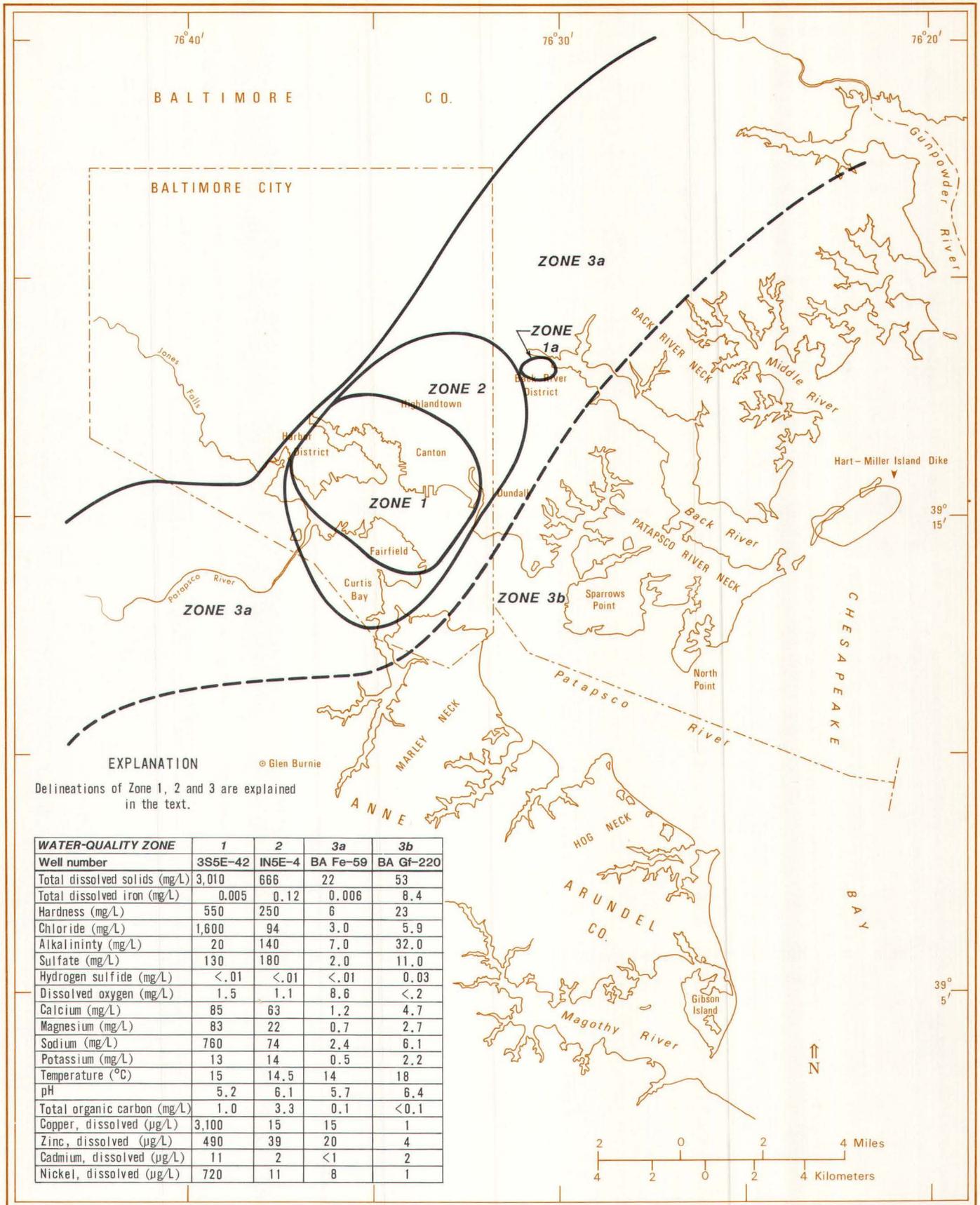
CHEMICAL EVOLUTION OF WATER IN THE PATUXENT AQUIFER

Background

Central to any discussion of water quality are the chemical processes that produce observed water composition. In the Baltimore area, water quality is strongly affected by brackish-water encroachment (zone 1, fig. 24) and urbanization-related contamination (zone 2, fig. 24). The question now remains as to what chemical processes govern water quality in the uncontaminated

**Table 6c.—Chemical-quality analyses of ground water from selected wells in the Patuxent aquifer—
Dissolved organic compounds—Continued**

2- Chloro- ethyl- vinyl- ether total (µg/L)	Carbon tetra- chloro- chloride total (µg/L)	Di- chloro- fluoro- methane total (µg/L)	Vinyl chloro- chloride total (µg/L)	Di- chloro- bromo- methane total (µg/L)	Tri- chloro- ethyl- ene total (µg/L)	Mala- thion total (µg/L)	USGS Well No.
Anne Arundel County (cont.)							
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	--	Ad 76
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	--	Ad 99
Baltimore County (cont.)							
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	--	Fe 59
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	--	Pf 85
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	--	Fg 69
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	--	Gf 210
Baltimore City (cont.)							
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	--	1N3E11
<1.0	<1.0	<1.0	<1.0	<1.0	10.0	--	1S3E46
<1.0	<1.0	<1.0	<1.0	<1.0	68.0	--	1S3E47
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	--	3S2E 5
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	--	3S5E35
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	--	3S5E39
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	--	
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	--	3S5E40
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	--	3S5E41
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	--	3S5E42
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	--	
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	--	3S5E43
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	--	3S5E44
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	--	5S2E20
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	--	5S2E24



Base map from the Maryland Geological Survey County Topographic Map Series, 1:62,500

Figure 24.—Water-quality zones of the Patuxent aquifer near Baltimore.

Table 7a.—Chemical-quality analyses of ground water from selected wells in the Patapsco aquifer—Major dissolved constituents and nutrients

USGS Well No.	Geologic unit	Date of sample	Silica, dissolved (mg/L as SiO ₂)	Oxygen, dissolved (mg/L)	Iron, dissolved (µg/l as Fe)	Calcium dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Alkalinity, field (mg/L as CaCO ₃)	Sulfate dissolved (mg/L as SO ₄)
Anne Arundel County											
Ad 41	217PPSC	11-19-81	9.1	6.7	19	6.2	2.4	8.1	1.9	<1.0	8.7
Ad 67	217PPSC	11-19-81	--	7.0	--	--	--	--	--	2.0	--
Ad 74	217PPSC	05-17-82	7.8	8.4	58	8.5	3.1	60	1.8	3.0	9.0
Bd 64	217PPSC	05-17-82	--	8.1	--	--	--	--	--	2.0	--
Bd 92	217PPSC	05-12-82	8.0	7.7	<9	2.1	1.0	2.2	.8	2.0	2.0
Bd 95	217PPSC	05-11-82	8.6	9.3	<3	14	1.9	5.1	.8	2.0	1.0
Baltimore County											
Eg 150	217PPSC	04-21-82	7.6	<.2	3300	.5	.6	1.2	.4	8.0	5.0
Fe 68	217PPSC	07-26-82	7.0	<.2	75	.5	.3	1.6	.2	5.0	1.0
Gf 168	217PPSC	12-02-81	--	.7	--	--	--	--	--	--	--
Gf 169	217PPSC	12-02-81	--	.8	--	--	--	--	--	--	--
Baltimore City											
3S5E46	217PPSC	11-23-82	12	0.6	1600	3.7	1.5	6.9	1.5	10	9.0
5S2E23	217PPSC	05-03-82	8.6	9.8	54	5.1	2.1	5.7	1.3	7.0	1.0
5S2E25	217PPSC	12-02-82	9.5	8.9	300	10	6.7	13	2.1	10	17
7S4E 2	217PPSC	04-07-82	9.8	.8	240	.8	.4	2.7	.5	<1.0	13

Table 7b.—Chemical-quality analyses of ground water from selected wells in the Patapsco aquifer—Minor and trace dissolved constituents

USGS Well No.	Geologic unit	Date of sample	Chromium dissolved (µg/L as Cr)	Fluoride, dissolved (mg/L as F)	Carbon, organic total (mg/L as C)	Arsenic dissolved (µg/L as As)	Barium, dissolved (µg/L as Ba)	Beryllium, dissolved (µg/L as Be)	Boron, dissolved (µg/L as B)	Cadmium dissolved (µg/L as Cd)
Anne Arundel County										
Ad 41	217PPSC	11-19-82	<1	<.1	.2	1	40	<1	<10	<1
Ad 74	217PPSC	05-17-82	5	<.1	.3	<1	100	<1	<20	1
Bd 64	217PPSC	05-17-82	--	--	.1	--	--	--	<20	--
Bd 92	217PPSC	05-12-82	<1	<.1	.9	1	21	<1	<20	<1
Bd 95	217PPSC	05-11-81	<1	<.1	.3	<1	20	<1	<20	<1
Baltimore County										
Eg 150	217PPSC	04-21-82	<1	<.1	.2	1	25	<1	20	<1
Fe 68	217PPSC	07-26-82	<1	<.1	.4	<1	10	<1	<10	<1
Baltimore City										
3S5E46	217PPSC	11-23-82	<1	<.1	.8	1	27	<1	30	<1
5S2E23	217PPSC	05-03-82	<1	<.1	.6	1	35	<1	<20	<1
5S2E25	217PPSC	10-02-82	3	<.1	1.1	1	99	<1	20	1
7S4E 2	217PPSC	04-07-82	12	<.1	.5	1	14	<1	<20	<1

Table 7c.—Chemical-quality analyses of ground water from selected wells in the Patapsco aquifer—Dissolved organic compounds

USGS Well No.	Date of sample	Geologic unit	1,2-Dichloroethane total (µg/L)	Bromoform total (µg/L)	Chloro-dibromo-methane total (µg/L)	Chloroform total (µg/L)	Toulene total (µg/L)	Benzene total (µg/L)	Chloro-benzene total (µg/L)	Chloro-ethane total (µg/L)	Ethyl-benzene total (µg/L)
Anne Arundel County											
Ad 41	07-15-82	217PPSC	<1.0	<1.0	<1.0	<1.0	<1.0	2.0	<1.0	<1.0	<1.0
Baltimore City											
3S5E46	11-23-82	217PPSC	<1.0	<1.0	<1.0	<1.0	4.0	<1.0	<1.0	<1.0	<1.0
5S2E23	07-14-82	217PPSC	9.0	<1.0	<1.0	<1.0	<1.0	3.0	<1.0	<1.0	<1.0
5S2E25	12-02-82	217PPSC	<1.0	<1.0	<1.0	8.0	12	<1.0	<1.0	<1.0	<1.0
7S4E 2	07-16-82	217PPSC	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0

**Table 7a.—Chemical-quality analyses of ground water from selected wells in the Patapsco aquifer—
Major dissolved constituents and nutrients—Continued**

Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Nitrate, dissolved (mg/L as N)	Nitrogen, ammonia & organics total (mg/L as N)	Nitrogen, total (mg/L as N)	Hydrogen sulfide, dissolved (mg/L as H ₂ S)	Solids, residue at 180°C dissolved (mg/L)	Solids, sum of constituents dissolved (mg/L)	Hardness (mg/L as CaCO ₃)	Specific conductance (µmhos 25°C)	pH (units)	Temperature (°C)	USGS Well No.
15	<.1	--	--	--	--	83	--	25	120	4.4	14.0	Ad 41
21.6	--	--	--	--	0.03	--	--	--	145	4.7	13.5	Ad 67
120	<.1	--	--	--	--	260	212	34	500	5.1	13.5	Ad 74
--	--	--	--	--	--	--	--	--	52	4.9	13.0	Bd 64
4.1	<.1	--	--	--	--	36	22	9	46	4.9	13.5	Bd 92
4.2	<.1	--	--	--	--	44	37	43	53	4.8	12.5	Bd 95
1.8	<.1	--	.27	--	0.03	22	25	4	34	5.5	15.0	Eg 150
1.7	<.1	--	--	--	--	18	16	3	20	5.4	15.0	Fe 68
425.0	--	--	--	--	--	--	--	--	2500	11.8	14.5	Gf 168
83	--	--	--	--	--	--	--	--	500	10.9	15.0	Gf 169
9.4	<.1	--	--	--	--	63	53	16	--	5.4	16.0	3S5E46
9.2	<.1	--	--	--	--	72	38	21	8	5.3	14.5	5S2E23
24	<.1	--	--	--	--	141	89	53	205	5.5	16.0	5S2E25
10	<.1	--	--	--	--	34	62	3	73	4.2	14.5	7S4E 2

**Table 7b.—Chemical-quality analyses of ground water from selected wells in the Patapsco aquifer—
Minor and trace dissolved constituents—Continued**

Cobalt, dissolved (µg/L as Co)	Copper, dissolved (µg/L as Cu)	Lead, dissolved (µg/L as Pb)	Manganese, dissolved (µg/L as Mn)	Molybdenum, dissolved (µg/L as Mo)	Nickel, dissolved (µg/L as Ni)	Silver, dissolved (µg/L as Ag)	Strontium, dissolved (µg/L as Sr)	Zinc, dissolved (µg/L as Zn)	Antimony, dissolved (µg/L as Sb)	Lithium, dissolved (µg/L as Li)	USGS Well No.
4	24	1	28	<1	7	<1	25	9	<1	6	Ad 41
5	9	4	45	<1	7	<1	52	53	<1	4	Ad 74
--	--	--	--	--	--	--	--	--	--	10	Bd 64
6	27	<1	16	<1	10	<1	9	37	<1	<4	Bd 92
3	8	1	<3	<1	8	<1	69	<12	<1	4	Bd 95
10	2	<1	91	<1	11	<1	3	58	<1	16	Eg 150
4	9	3	7	<1	3	<1	2	94	<1	<4	Fe 68
8	<1	2	98	<1	10	<1	22	270	2	10	3S5E46
1	19	11	9	<1	<1	<1	25	850	<1	<4	5S2E23
8	8	12	120	<1	6	<1	84	210	<1	<4	5S2E25
8	24	5	17	<1	16	<1	<6	77	<1	4	7S4E 2

**Table 7c.—Chemical-quality analyses of ground water from selected wells in the Patapsco aquifer—
Dissolved organic compounds—Continued**

Methylbromide total (µg/L)	Methylene chloride total (µg/L)	Tetrachloroethylene total (µg/L)	Trichloroethylene total (µg/L)	1,1-Dichloroethane total (µg/L)	1,1-Dichloroethene total (µg/L)	1,1,1-Trichloroethane total (µg/L)	1,1,2-Trichloroethane total (µg/L)	1,1,2,2-Tetrachloroethane total (µg/L)	1,2-Dichloropropane total (µg/L)	Chloroethylene total (µg/L)	1,3-Dichloropropane total (µg/L)	USGS Well No.
Anne Arundel County												
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	Ad 41
Baltimore City												
<1.0	4.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	3S5E46
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	5S2E23
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	8.0	<1.0	<1.0	<1.0	5S2E25
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	7S4E 2

part of the aquifer (zone 3, fig. 24). In many respects, this is the most important question because zone 3 covers by far the greatest area near Baltimore. The purpose of this section of the report is to investigate the chemical processes that determine Patuxent aquifer water quality. This discussion is limited to the Patuxent aquifer primarily because of the lack of available Patapsco aquifer water analyses. However, because the lithology of the aquifers are similar, it is reasonable to expect that the operative chemical processes also will be similar.

The chemical composition of Patuxent aquifer water changes systematically along the hydrologic gradient. Near the outcrop area (zone 3a, fig. 24) the water contains measurable concentrations of dissolved oxygen (1 to 10 mg/L), low concentrations of dissolved iron (0.01 mg/L), low concentrations of sulfate (2.0 mg/L), and a relatively low pH (4.5 to 5.5). Downgradient (zone 3b, fig. 24), dissolved oxygen concentrations decrease below measurable levels, dissolved iron and sulfate concentrations increase, and pH increases. There is an increase in total dissolved solids along the flow-path. In order to identify the chemical processes that cause this observed distribution of dissolved species, the following procedures will be used:

- (1) Document concentration changes of dissolved species as a function of distance along the hydrologic gradient.
- (2) Relate these concentration changes to aquifer lithology and mineralogy.
- (3) Construct stoichiometric chemical models to explain the observed changes in water composition.
- (4) Use equilibrium chemistry calculations and solute-stability diagrams to determine the speciation of dissolved iron.

Lithology and Chemical Microenvironments

In order to evaluate the chemistry of Patuxent aquifer water, it is important to consider the aquifer's complex mineralogy and lithology. The Patuxent aquifer consists of many small-scale fining-upward sequences that are superimposed on an overall fining-upward trend. This lithology reflects fluvial sedimentation that occurred under conditions of steadily decreasing stream gradients. This complex aquifer lithology will be reflected in the chemistry of Patuxent aquifer water. It is reasonable to expect that water in contact with organic-rich, fine-grained sediment will differ in composition from water in contact with clean, well-sorted gravel. In the Patuxent aquifer, these chemical "microenvironments" characteristically occur within tens of feet of each other. In view of this, it is more accurate to describe the Patuxent aquifer as an assemblage of chemical microenvironments than as a homogeneous chemical system. As water flows down the hydrologic gradient, overall changes in water composition will reflect the cumulative effects of these microenvironments.

Quartz in the form of sand and gravel is by far the most abundant mineral in the Patuxent aquifer. Associated with the sand and gravel are discontinuous lenses of kaolinitic and illitic clays. It is estimated that silt- and clay-sized material makes up between 5 and 10 percent of aquifer material in the Baltimore area. Feldspars are present in very small amounts that total less than 1 percent of aquifer material. Pyrite and ferric hydroxides are the most abundant iron-bearing minerals. Pyrite generally is associated with lignitic material. The ferric hydroxides often occur as coatings on quartz grains or as a cement matrix. Heavy minerals such as kyanite, rutile, and garnet comprise less than 1 percent of total aquifer material.

Table 7c.—Chemical-quality analyses of ground water from selected wells in the Patapsco aquifer—Dissolved organic compounds—Continued

2-Chloro-ethyl-vinyl-ether total ($\mu\text{g/L}$)	Carbon tetra- chloride total ($\mu\text{g/L}$)	Di-chloro-fluoro-methane total ($\mu\text{g/L}$)	Vinyl chlo-ride total ($\mu\text{g/L}$)	Di-chloro-bromo-methane total ($\mu\text{g/L}$)	Tri-chloro-ethyl-ene total ($\mu\text{g/L}$)	Mala-thion total ($\mu\text{g/L}$)	USGS Well No.
Anne Arundel County							
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	--	Ad 41
Baltimore City							
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	--	3S5E46
<1.0	<1.0	<1.0	<1.0	<1.0	11.0	--	5S2E23
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	--	5S2E25
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	--	7S4E 2

All of the minerals in the Patuxent will react to some degree with ground water. The complexity of the mineralogy and mineral-water interactions makes it impossible to construct an exact model of water chemistry. However, the effects of slow-reacting minerals will be small compared to the effects of fast-reacting minerals. The approach taken in this report is to assume that the fast-reacting minerals have a much greater impact on water chemistry than slow-reacting minerals. If this assumption results in an acceptable approximation, then the reaction models that are constructed will be nonunique, but nevertheless useful.

Under ambient temperature, pressure, and pH conditions in the Patuxent aquifer, quartz can be expected to react relatively slowly. Similarly, the oxide and silicate heavy minerals will react relatively slowly. For the purpose of this report, these phases will be considered nonreactive. Iron minerals, such as pyrite and iron hydroxides, react very rapidly in most ground-water systems. This is particularly true if changes in redox conditions occur as water moves through the aquifer. These mineral phases can, therefore, be expected to have a major impact on Patuxent aquifer water chemistry. Silicate minerals such as plagioclase, orthoclase, and clay minerals are highly reactive in many ground-water systems. Because these minerals readily undergo hydrolysis reactions, they are effective pH-buffering agents. These reactions are fairly rapid and may have a major influence on Patuxent aquifer water. An important lithologic constituent of the Patuxent aquifer is lignite. Lignite is a strong reducing agent and reacts very rapidly under most conditions. Lignite can be expected to have a major impact on Patuxent water chemistry. Certain gases will also be important in the chemical evolution of Patuxent water. Oxygen and carbon dioxide are present in soil gas and can react with percolating water in the soil zone. Carbon dioxide can also be generated in the aquifer by slow oxidation of lignite. Finally, hydrogen sulfide gas can be generated in the aquifer by sulfate reduction. All of these reactions occur rapidly and may significantly affect Patuxent aquifer water chemistry.

Distribution of Dissolved Species

One convenient method of showing water-chemistry changes in an aquifer is to graph concentrations of dissolved species as a function of distance along a flowpath. This method has the advantage of showing overall water-composition changes on a regional scale. Also, the scatter of data points around overall trends gives an indication of water-composition variability in the aquifer. In the Patuxent aquifer, the distance that water has moved along flowpaths can be estimated from the prepumping potentiometric surface (fig. 6a). As a matter of convention, the southern limit of the outcrop area can be chosen as zero distance.

The concentrations of total dissolved solids (TDS), dissolved oxygen (DO), sulfate ($\text{SO}_4^{=}$), iron, pH, and alkalinity plotted versus distance along the flowpath are shown in figure 25. Plotting the data in this manner reveals several trends.

- (1) Concentrations of total dissolved solids are very low near the outcrop area and increase downgradient.
- (2) Concentrations of dissolved oxygen are high near the outcrop area and decrease sharply downgradient. By 6 mi downgradient, there is little or no measurable dissolved oxygen in the water.
- (3) Concentrations of sulfate are low in the outcrop area and increase sharply downgradient. Sulfate concentrations appear to level off at about 6 mi downgradient.
- (4) Dissolved iron concentrations are low near the outcrop area. They remain relatively low until about 6 mi downgradient, where they increase sharply.
- (5) pH is about 5.5 in the outcrop area, and, by 2 mi downgradient, decreases to about 4.5. Beyond 2 mi, there is a steady trend of rising pH.
- (6) Alkalinity is low in the outcrop area and remains low until about 6 mi downgradient. The alkalinity then rises sharply.

In addition to showing general trends in water-composition change, an estimate of local variability can be made from the data scatter. Dissolved oxygen shows the widest variability with individual data points near the outcrop area deviating by ± 4 mg/L. Downgradient, this variability is not evident. The other plots show that, in general, the data points cluster fairly tightly about the overall trends. The observed variability in water composition is probably due to chemical micro-environments associated with complex aquifer lithology and uncertainties about the exact distance that water has moved along the flowpath.

In addition to the water-composition changes shown in figure 25, there are slight increases (on the order of 2 or 3 mg/L each) of dissolved calcium, magnesium, sodium, and potassium. Silica concentrations remain nearly constant at about 9 mg/L.

The patterns of concentration changes shown in figure 25 are important for two reasons. First, they suggest that water composition in the Patuxent aquifer can be estimated based on distance along the flowpath. This observation may be of considerable value to water planners considering well-field siting. Secondly, the systematic nature of the concentration changes suggests that

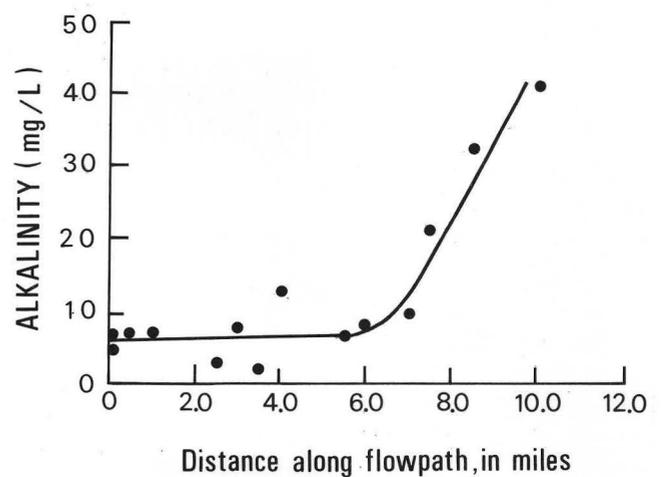
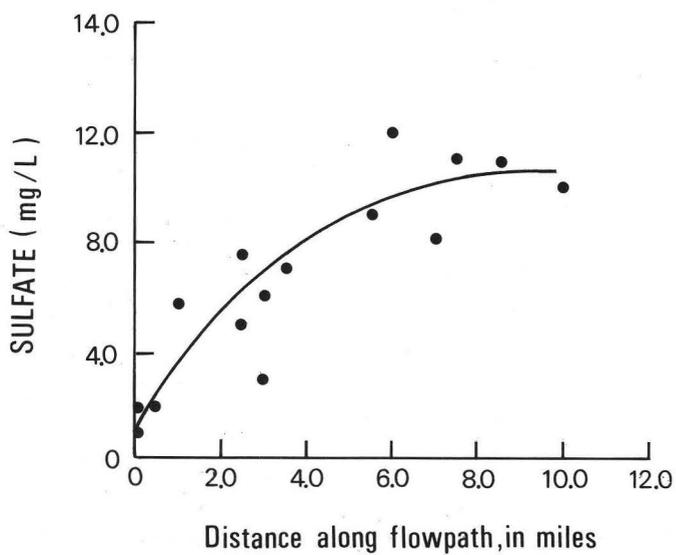
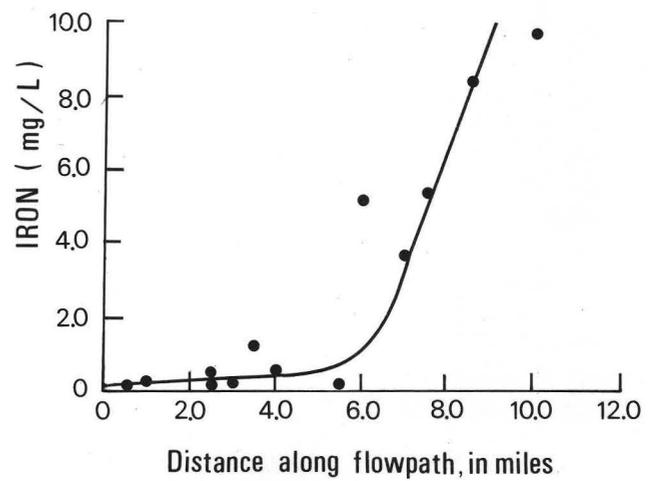
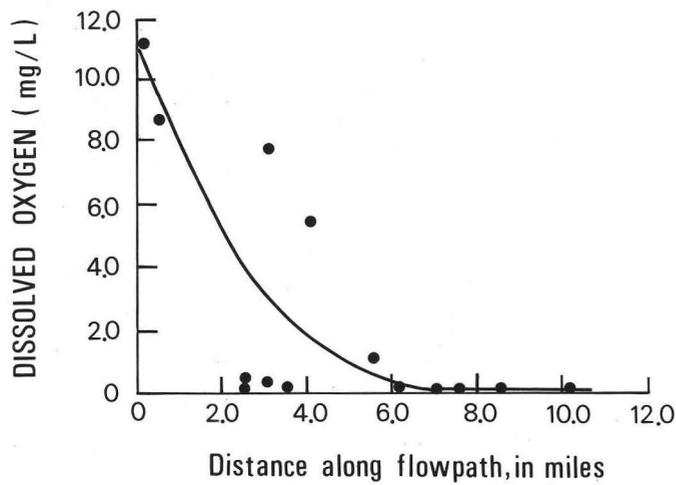
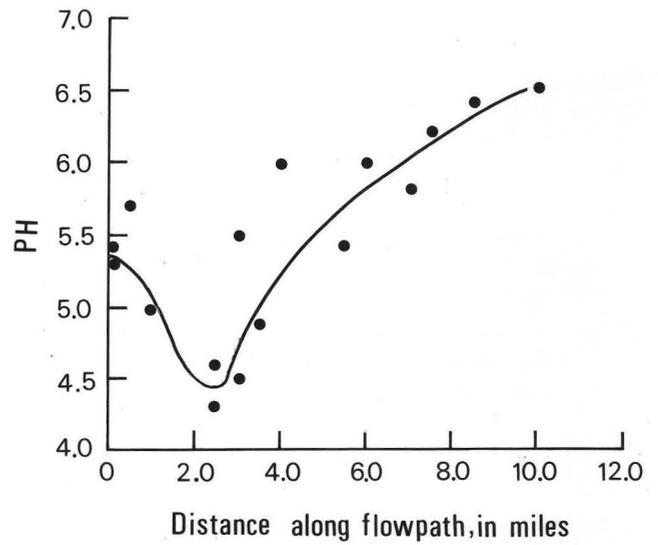
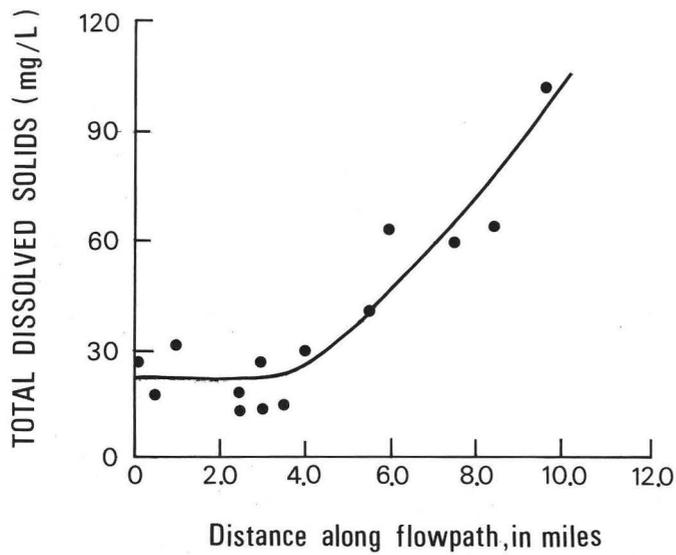


Figure 25. — Concentrations of selected constituents versus distance along the flowpath.

water composition is being regulated by geochemical processes. The next step in this analysis, therefore, is to investigate these processes.

Development of Working Equations

The lithology of the Patuxent aquifer suggests that lignite, pyrite, ferric hydroxides, and silicate minerals have the most effect on the natural water chemistry. In order to treat these effects quantitatively, equations that describe the reaction of each phase with water must be developed. This type of analysis is non-exact because of uncertainties in mineral compositions. It is possible, however, to assign generalized compositions for most minerals.

Lignite is a term referring to organic material that has undergone varying degrees of oxidation. As such, it represents a variety of compositions. Freeze and Cherry (1979, p. 117) accept the generalized composition, CH_2O , for this phase. In the absence of more precise data, this composition will be used in this report. Under this assumption, the reaction of lignite with oxygenated water can be written:



Equation 12 is valid only when the pH is below 5.5 and undissociated CO_2 is the predominant species (Hem, 1970, p. 155). Above pH 5.5, bicarbonate ion is predominant and the reaction must be written:

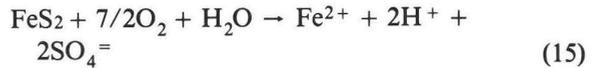


In the absence of free oxygen, organic matter will reduce sulfate according to the equation:

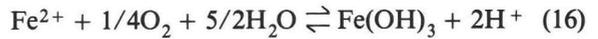


This reaction is normally catalyzed by microbial organisms.

Pyrite is unstable in oxygenated water and will react according to the equation:



Dissolved Fe^{2+} ions produced by this reaction are also unstable in oxygenated water and will react so that:



In the absence of free oxygen, the reverse of equations 15 and 16 apply.

Silicate minerals present difficulties in developing chemical equations of this type. This is due primarily to the wide compositional ranges exhibited by many classes of silicates. Also, because silicate dissolution commonly is incongruent, the nature of the stable weathering products affects water-composition changes. Although it is difficult to evaluate silicate compositional variation, it is relatively easy to determine the stable weathering products from chemical equilibrium considerations. The stability relationships of Patuxent aquifer water for gibbsite, kaolinite, montmorillonite, muscovite, and feldspars are plotted in figure 26. Stabilities in the

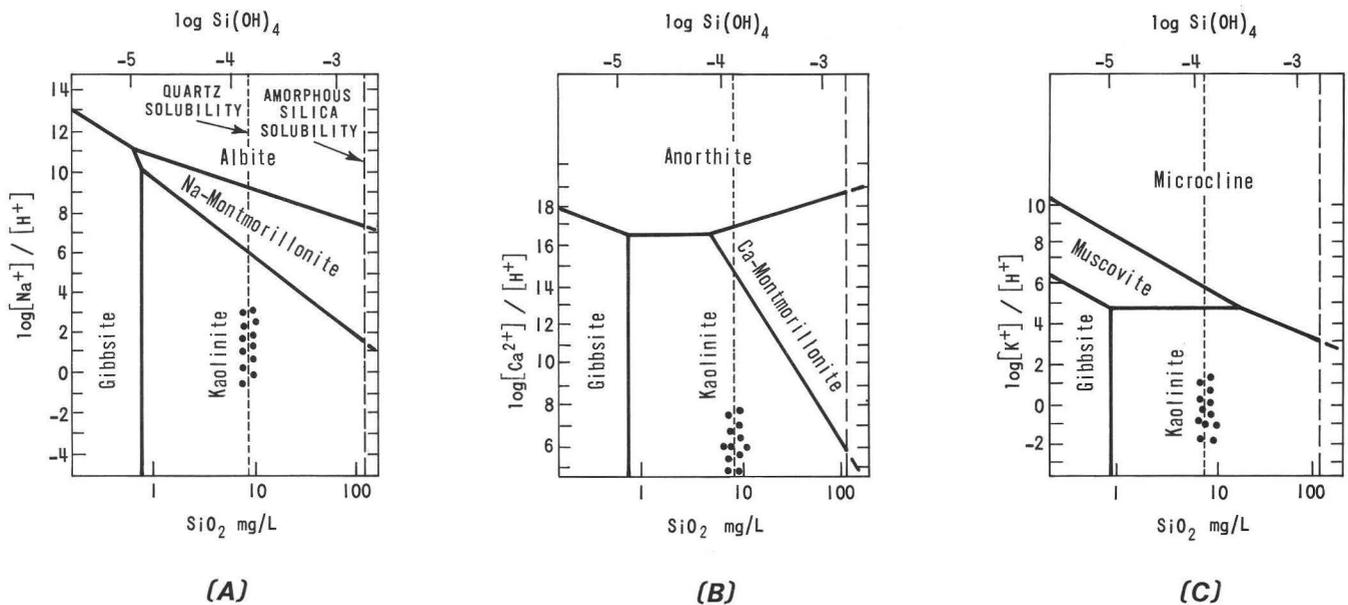
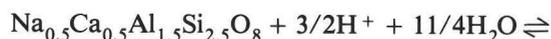


Figure 26.—Patuxent aquifer water analyses plotted on silicate mineral-stability diagrams.

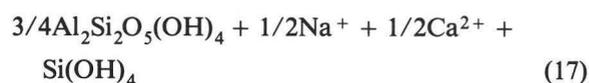
systems $\text{Na}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$, $\text{CaO}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$, and $\text{K}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$ are considered. The data plotted on these stability diagrams demonstrate that kaolinite should be the stable weathering product of silicate minerals in the Patuxent aquifer.

Freeze and Cherry (1979, p. 270) tabulate the stoichiometry of some silicate minerals that weather to kaolinite. Because it has been demonstrated that kaolinite should be the stable weathering product in the Patuxent, Freeze and Cherry's (1979) equations will be used in this report. The reaction of plagioclase ($\text{An}_{50}\text{Al}_{50}$) to kaolinite is written:

Plagioclase

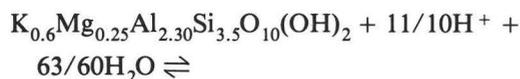


Kaolinite

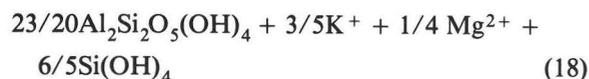


Similarly, the illite-kaolinite reaction may be written:

Illite



Kaolinite

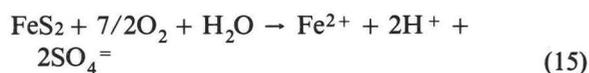


Although these equations represent idealized mineral compositions, they may be applied in qualitatively in considering silicate hydrolysis.

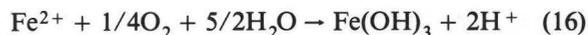
Chemical Reaction Models

In the simplified system used to develop working equations, dissolved $\text{SO}_4^{=}$ and H^+ ions are produced by pyrite oxidation (eq. 15). Dissolved oxygen, on the other hand, is consumed by oxidation of pyrite, Fe^{2+} , and lignite (eqs. 12, 15, and 16). These equations can now be combined to account for observed water-chemistry changes in zone 3a of the Patuxent aquifer.

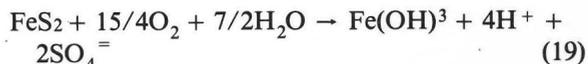
The data of figure 24 indicate that a source of $\text{SO}_4^{=}$ ions and a sink for dissolved oxygen is required. The process of pyrite oxidation as expressed by equation 15 is a source of $\text{SO}_4^{=}$ and also consumes dissolved oxygen.



However, because Fe^{2+} concentrations are low, there must be a sink for Fe^{2+} . Equation 16 is such a sink. Note that the reaction represented by equation 16 also consumes dissolved oxygen.



Adding equations 15 and 16 algebraically yields:



This equation predicts that dissolved oxygen will be consumed at 1.88 times the molar amount of $\text{SO}_4^{=}$ produced. Thus, if dissolved oxygen concentrations are plotted against $\text{SO}_4^{=}$ concentrations, the result should be a line with slope -1.88. Figure 27 shows such a plot for zone 3a water analyses. The observed slope of this plot is -3.1, considerably greater than predicted by equation 19. This suggests that dissolved oxygen, in addition to being consumed by pyrite and Fe^{2+} oxidation, is being consumed by an additional process. In this system, oxidation of lignite is such a process. Since the pH of zone 3a water is generally lower than 5.5, equation 12 applies:

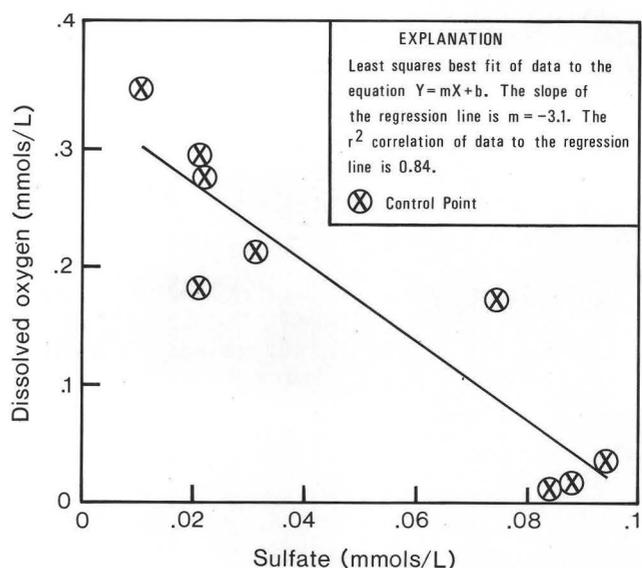
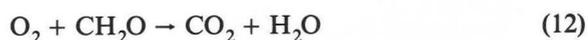
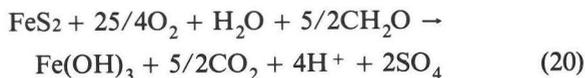


Figure 27.—Dissolved oxygen concentrations plotted against sulfate concentrations for zone 3a water.

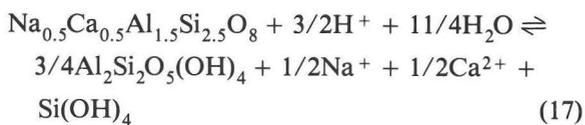
Because pCO_2 was not directly measured in Patuxent aquifer water, the relative amount of CO_2 produced to

O₂ consumed cannot be deduced with available data. However, an estimate of O₂ consumed by lignite oxidation can be obtained by simple stoichiometry. Adding equation 19 and equation 12 algebraically and balancing the coefficients so that the ratio of dissolved oxygen consumed to SO₄⁻ produced is about 3.1:

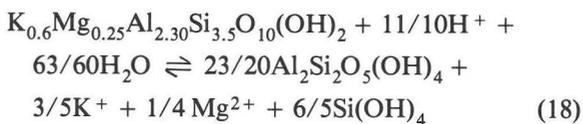


Thus, based on limited data, it appears that about 2 1/2 moles of CH₂O is oxidized for each mole of pyrite oxidized. Regardless of the stoichiometry of this, however, equation 20 explains the rapid consumption of dissolved oxygen. Given the simplifying assumptions made in developing the working equations, equation 20 is a stoichiometric model for the ground-water chemistry of zone 3a. Because of the limited data available for estimating the relative impact of lignite on dissolved oxygen consumption, equation 20 must be regarded as approximate. More complete data in the future may result in an improvement of equation 20.

Equation 20 predicts that the pH of the system should decrease in zone 3a. Figure 25 shows that pH does decrease initially, but then rises. The pH rise is probably produced by the pH-buffering effects of silicate minerals. Hydrolysis of silicates to kaolinite consumes H⁺ ions:



and:

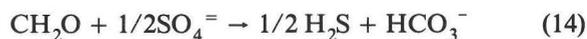


The stoichiometry of these processes cannot be precisely defined with available data for two reasons. First, the compositional ranges of silicates in the Patuxent are poorly known. Secondly, because concentrations of H⁺ ions typically are one to two orders of magnitude less than Ca²⁺, Mg²⁺, Na⁺, K⁺, or Si(OH)₄ concentrations, even a large pH change will be accompanied by little measurable change of the other species. Therefore, on the basis of the increasing pH, it can be hypothesized that silicate hydrolysis reactions are important processes. However, this cannot be verified on the basis of ion stoichiometrics.

As water moves downgradient from zone 3a to zone 3b, all measurable dissolved oxygen has been consumed. At this point, equations 12, 15, and 16 cannot

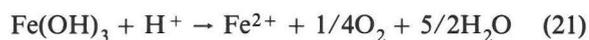
proceed from left to right and the reaction model represented by equation 20 is no longer applicable.

In zone 3b, concentrations of alkalinity and dissolved iron increase substantially. Three processes may be contributing to the observed alkalinity increase. Below pH 5.5, carbon dioxide is present primarily as undissociated CO₂. Farther than 6 mi downgradient, Patuxent water is generally above pH 5.5. In this case, dissolved HCO₃⁻ would be the predominant species (eq. 13) and could therefore contribute acid-neutralizing capacity (alkalinity) to the water. The second possible process is sulfate reduction. In the absence of free dissolved oxygen, sulfate may be reduced by lignite to produce bicarbonate and hydrogen sulfide.



Many wells in zone 3b produce water that contains measurable concentrations of hydrogen sulfide (table 6a). This is direct evidence that sulfate reduction is an operative process in downgradient areas. Finally, alkalinity may be produced by hydrolysis of silicates. It is likely that the observed sharp increase in alkalinity results from a combination of these three processes.

The observed increase in dissolved iron concentration probably is due to the lack of free dissolved oxygen. Under reducing conditions, Fe²⁺ is stable in solution and may be produced by reduction of ferric hydroxide:



or by hydrolysis of iron-bearing silicates. The geochemistry of dissolved iron in this system is discussed in more detail in a following section.

Iron Cementation

Ledges of iron hydroxide-cemented sandstone and conglomerate are a conspicuous lithologic feature of the Patuxent aquifer. The presence of iron cementation follows two general patterns. On a regional scale, iron cementation is much more abundant in and near outcrop areas. For example, Glaser (1969, p. 38) observes:

Gravels are in many instances thoroughly lithified by hematite or limonite cement. Such cementation . . . is virtually restricted to the near surface.

Additional evidence for this pattern can be found in the logs of water wells drilled near Baltimore (Bennett and Meyer, 1955, p. 311-447). These logs reveal that "rock" or iron-cemented ledges are common near the outcrop area, but less common downgradient. In individual outcrops, however, the iron cementation follows another

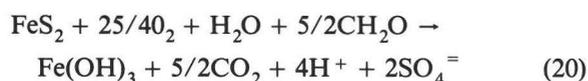
pattern. Glaser (1969, p. 60) suggests iron cement tends to be related to permeability:

The abundance of iron oxide cements is correlated in part with permeability. For example, partial to complete cementation of gravel and coarse sand is a much more common phenomenon than cementation of medium and fine sand.

It is also commonly observed in outcrops that the iron cement is present at the contact between more permeable and less permeable beds.

Glaser (1969, p. 60) interprets much of the observed iron cementation as being postdepositional. Glaser further suggested that the cementation is related to the action of ground water. If this is true, then the stoichiometric model derived for the water chemistry of zone 3a should be consistent with the observed patterns of cementation.

In the oxygenated zone 3a of the Patuxent aquifer, it has been shown that on a regional scale, the consumption of dissolved oxygen can be described by the equation:



This equation is based solely on observed changes in water chemistry along the flowpath. This equation predicts, however, that solid ferric hydroxide will be produced as dissolved oxygen is consumed. Inspection of equation 20 reveals that about 6 moles of dissolved oxygen is required to produce 1 mole of ferric hydroxide. It follows that significant amounts of ferric hydroxide should coincide with the greatest observed decline in dissolved oxygen concentrations. Figure 25 shows that dissolved oxygen concentrations decrease the most within 2 mi of the outcrop area. Equation 20 predicts, therefore, that much of the iron cementation should be restricted to near the outcrop area. This is consistent with the observed distribution of the cementation.

The model of dissolved oxygen consumption and ferric hydroxide cementation (eq. 20) is meaningful only at the regional scale. The water-chemistry data used to construct the model reflect concentration changes along a regional flowpath. These average changes reflect the sum of many small-scale changes produced by chemical microenvironments. While it can be argued that the stoichiometries of the small and regional scale processes are similar, data are not available to test this directly.

The concept of chemical microenvironments can be used to explain patterns of iron cementation that are observed on an outcrop scale. It is likely, for example, that water in silty beds containing finely disseminated lignite will be strongly reducing. As such, significant concentrations of Fe^{2+} may be stable in solution. Tens

of feet away in coarse gravel beds without lignite, the water may contain free dissolved oxygen and, therefore, be strongly oxidizing. If water from these two zones are mixed, Fe^{2+} will precipitate according to the reaction:



and produce iron cementation. Because mixing of water from these two zones would occur at the contact between coarse- and fine-grained beds, iron cementation at the contact is to be expected. This model, therefore, is consistent with the observation that cementation occurs at the contacts between coarse and fine beds. Also, because the permeable gravel beds are more likely to contain dissolved oxygen, cementation of these beds is more likely. The model of chemical microenvironments is therefore consistent with many patterns of iron cementation that are observed in outcrop.

GEOCHEMISTRY OF DISSOLVED IRON

Background

From a water-quality standpoint, dissolved iron is one of the more important constituents in Patuxent and Patapsco aquifer water. Water containing more than about 0.1 mg/L dissolved iron may have an "irony" taste and may stain plumbing fixtures. For these reasons, high concentrations of dissolved iron are considered objectionable. The data of table 6a show that Patuxent and Patapsco water commonly contains more than 0.1 mg/L dissolved iron. Some of the geochemical processes that contribute to such high iron concentrations have been discussed previously in a general context. It is appropriate at this point to develop a closer understanding of the occurrence and speciation of dissolved iron in the Patuxent and Patapsco aquifers.

Redox Buffering

In order to evaluate the speciation of dissolved iron, information on the oxidation-reduction (redox) potential of the system is required. While there are severe operational difficulties in directly measuring redox potential, the concept is nevertheless very useful in expressing mineral and solute stabilities. Redox potential, as expressed by Eh or pE, is well known in the geochemical literature (Hem, 1970, p. 28-30). In contrast, the concept of redox buffering has received much less attention. The term "buffer" in chemistry comes from the word "buff" — to deaden the shock. A chemical system is said to be buffered if concentrations of components are maintained at about the same level despite changes to the system. Geologists are probably

most familiar with the concept of buffering as it applies to pH (Hem, 1970, p. 92). Earlier in this report, for example, it was shown how water can be pH-buffered by carbonic acid dissociation (eq. 13) or by silicate hydrolysis (eqs. 17 and 18).

A chemical system may be buffered with respect to redox potential in a manner analogous to pH-buffering (Drever, 1982, p. 282–284). For example, water containing free dissolved oxygen is buffered by the reaction:



Forming the reaction quotient of equation 22 yields:

$$\frac{[\text{H}_2\text{O}]}{[\text{O}_2]^{1/2} [\text{H}^+]^2 [\text{e}^-]^2} = K_{\text{eq}}; \quad K_{\text{eq}} = 3.63 \times 10^{41} \quad (23)$$

Setting the activity of H_2O to unity, taking logs, and solving for $-\log [\text{e}^-]$:

$$-\log [\text{e}^-] = 1/2 (1/2 \log [\text{O}_2] + 2 \log [\text{H}^+] = \log K_e) \quad (24)$$

Since $-\log [\text{e}^-] = \text{pE}$ and $-\log [\text{H}^+] = \text{pH}$, equation 24 may be written:

$$\text{pE} = 1/4 \log [\text{O}_2] - \text{pH} + 1/2 \log K_e. \quad (25)$$

At $\text{pH} = 7.0$ and $[\text{O}_2] = 10 \text{ mg/L}$, the water has a pE of $+12.9$. If concentrations of dissolved oxygen decrease two orders of magnitude, the pE drops only to $+12.4$. These calculations demonstrate that the redox potential of oxygenated water remains relatively high despite large changes in dissolved oxygen concentrations. In other words, pE is buffered by the $\text{O}_2/\text{H}_2\text{O}$ couple as expressed by equation 22.

Other redox couples that may buffer redox potential in ground-water systems include $\text{MnO}_2/\text{Mn}^{2+}$, $\text{Fe}(\text{OH})_3/\text{Fe}^{2+}$, and $\text{SO}_4^{2-}/\text{H}_2\text{S}$ (Drever, 1982, p. 293). In the Patuxent and Patapsco aquifers, manganese concentrations are generally low (table 6b, 7b). It is unlikely, therefore, that the $\text{MnO}_2/\text{Mn}^{2+}$ couple contributes substantial redox buffer capacity to this system. It is probable that $\text{O}_2/\text{H}_2\text{O}$, $\text{Fe}(\text{OH})_3/\text{Fe}^{2+}$, and $\text{SO}_4^{2-}/\text{H}_2\text{S}$ are the most important redox buffer couples in these aquifers.

Figure 28, which is modified from Drever (1982, p. 284), summarizes the effects that the $\text{O}_2/\text{H}_2\text{O}$, $\text{Fe}(\text{OH})_3/\text{Fe}^{2+}$, and $\text{SO}_4^{2-}/\text{H}_2\text{S}$ redox couples may have on ground-water systems. It is assumed that lignite is the dominant reducing agent in the aquifer. Figure 28 illustrates an extremely important result of redox buffering. The pE is either high (buffered by the $\text{O}_2/\text{H}_2\text{O}$

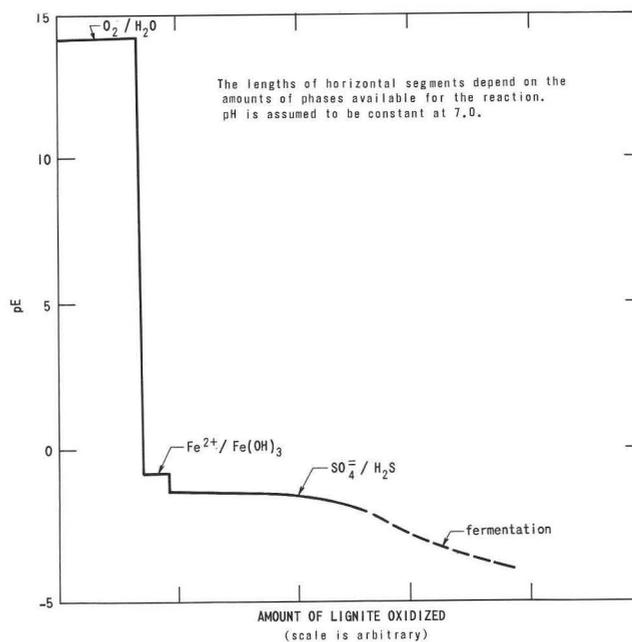


Figure 28.—Change in pE of water in contact with sediment as a function of the amount of lignite oxidized.

couple) or it is low (buffered by either the $\text{Fe}(\text{OH})_3/\text{Fe}^{2+}$ or $\text{SO}_4^{2-}/\text{H}_2\text{S}$ couple). There is no intermediate pE possible under equilibrium conditions. In the Patuxent and Patapsco aquifers, pE will be high where free dissolved oxygen is present. Once the dissolved oxygen has been consumed, however, the pE will be low. This change in pE will be accompanied by changes in mineral and solute stabilities.

Equilibrium Chemistry

The geochemistry of dissolved iron in ground-water systems is extremely complex. Much of this complexity arises from the many different dissolved ionic species that iron can form. Depending on solution composition, temperature, pH , and pE conditions, such species as Fe^{2+} , Fe^{3+} , $\text{Fe}(\text{OH})^{2+}$, $\text{Fe}(\text{OH})_2^+$, or $\text{Fe}(\text{OH})_4^-$, to name a few, may be stable. Ten to fifteen different ionic species may contribute to total dissolved iron in ground water. It is important to realize that a dissolved iron concentration given by chemical analysis represents the *sum* of all the dissolved iron species that are present. Thus, based simply on a water analysis, it is not possible to determine which iron species are present or what their relative proportions are. The chemistry is further complicated by the many different iron minerals that may be present in the aquifer. In the Patuxent and Patapsco aquifers, ferric hydroxide, goethite, hematite, iron silicates, and pyrite are the most common iron

minerals. The stability of these phases is not always certain because they commonly have ranges of composition.

Faced with these complexities and uncertainties, it is evident that iron speciation is not a problem amenable to an exact solution. It is possible, however, to make some useful generalizations. The approach taken here will be to evaluate iron speciation in the Patuxent and Patapsco aquifers based on equilibrium chemistry considerations. The goal of this effort will be to determine which iron species are predominant in solution for given chemical conditions. It may be anticipated that because chemical conditions in the aquifers change as water flows downgradient, the iron speciation also may change.

The chemical equilibrium approach to the speciation problem can be illustrated very simply. The following example is modified from Nordstrom and others (1979). Assuming a solution contains free Fe^{2+} and OH^- ions and the ion pair $\text{Fe}(\text{OH})^+$, and assuming that the total iron and total hydroxide concentrations in solution are known from chemical analysis, the mass balance of the system is then given by:

$$m\text{Fe}_{(\text{total})} = m\text{Fe}^{2+} + m\text{Fe}(\text{OH})^+ \quad (26)$$

and:

$$m\text{OH}_{(\text{total})} = m\text{OH}^- + m\text{Fe}(\text{OH})^+ \quad (27)$$

At equilibrium, the restriction:

$$K_{\text{eq}} = \frac{[\text{Fe}(\text{OH})^+]}{[\text{Fe}^{2+}] [\text{OH}^-]} \quad (28)$$

also applies. Substituting equation 28 into equations 26 and 27 gives:

$$m\text{Fe}_{(\text{total})} = m\text{Fe}^{2+} + K_{\text{eq}}(m\text{Fe}^{2+})(m\text{OH}^-) \quad (29)$$

and:

$$m\text{OH}_{(\text{total})} = m\text{OH}^- + K_{\text{eq}}(m\text{Fe}^{2+})(m\text{OH}^-) \quad (30)$$

Because $\text{Fe}_{(\text{total})}$, $\text{OH}_{(\text{total})}$, and K_{eq} are known, the concentrations of $m\text{Fe}^{2+}$ and $m\text{OH}^-$ can be calculated by simultaneous solutions of equations 29 and 30. This is generally accomplished by an iterative procedure based on successive approximations.

In natural systems many more dissolved iron species are present. The total number of simultaneous equations, therefore, depends on the number of species considered. Several different chemical equilibrium models, which use computers to solve the simultaneous

equations, are presently available. One such program, WATEQF¹ (Plummer and others, 1978) was used for this report. It should be evident from the preceding discussion that the accuracy of the calculated speciation depends on several factors:

- (1) The accuracy of available chemical analysis.
- (2) The accuracy of thermochemical data used to calculate equilibrium constants.
- (3) The degree to which the natural system has approached equilibrium.

Given the uncertainties inherent in this type of analysis, it was judged that WATEQF would be used primarily to determine the predominant dissolved iron species for different conditions. Also WATEQF was used to estimate the stabilities of different iron minerals for different conditions.

It has been shown that as Patuxent aquifer water flows downgradient, dissolved oxygen is consumed. From 0 to about 6 mi along the flowpath, Patuxent water contains free dissolved oxygen. Therefore, the pE of the system will be buffered at about 16.5 (for pH = 5.0). Beyond 6 mi downgradient, Patuxent water is anoxic and pE is buffered by the $\text{Fe}^{2+}/\text{Fe}(\text{OH})_3$ and $\text{SO}_4^{2-}/\text{H}_2\text{S}$ couples to about -2.5. Table 8 shows the calculated equilibrium speciation of dissolved iron for water analyses from wells BA-Fc 51 and BA-Gf 220. Water from well BA-Fc 51 contained measurable concentrations of dissolved oxygen, whereas water from BA-Gf 220 contained no measurable dissolved oxygen. Redox conditions for BA-Fc 51 water were calculated by WATEQF using the $\text{O}_2/\text{H}_2\text{O}$ couple. Redox conditions for BA-Gf 220 water were calculated with the $\text{SO}_4^{2-}/\text{H}_2\text{S}$ couple.

Table 8 shows a significant difference in iron speciation between the water of the two wells. For the oxic water, $\text{Fe}(\text{OH})_2^+$ is the predominant form of dissolved iron. Fe^{2+} is not present in measurable quantities. For the anoxic water, however, Fe^{2+} is the predominant dissolved species and $\text{Fe}(\text{OH})_2^+$ is a very minor component. There are also significant differences in mineral stabilities. The oxic water is supersaturated with respect to ferric hydroxide. The anoxic water, on the other hand, is undersaturated with respect to ferric hydroxide.

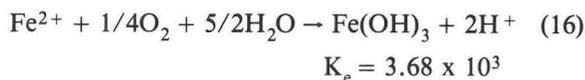
One of the disadvantages of using a program such as WATEQF is that water analyses can be dealt with one at a time. However, given the information that $\text{Fe}(\text{OH})_2^+$ should be the predominant dissolved species in oxic waters, it is possible to test if analyses of other oxic water conforms to this pattern. Assuming ferric

¹WATEQF stands for WATER EQUILIBRIUM.

Table 8.—Chemical speciation of dissolved iron in oxic and anoxic water as calculated by WATEQF

Dissolved species	Concentrations of dissolved species (Units are log molality)	
	Oxic water (Well BA-Fe-51)	Anoxic water (Well BA-Gf-220)
O ₂	- 3.73	< - 5.50
H ₂ S	< - 6.53	- 6.14
SO ₄ ⁼	- 4.69	- 3.96
Total Fe	- 5.30	- 3.82
Fe ²⁺	-13.55	- 3.90
Fe ³⁺	-10.63	-19.62
Fe(OH) ²⁺	- 7.81	-15.59
Fe(OH) ⁺	-18.10	- 7.23
Fe(OH) ₃ ⁻	-29.33	-16.23
Fe(OH) ₂ ⁺	- 5.31	-12.31
Fe(OH) ₃ ^o	- 7.86	-13.84
Fe(OH) ₄ ⁻	-10.44	-15.44
Fe(OH) ₂ ^o	-24.26	-12.17
FeSO ₄ ⁺	-11.69	-19.8
FeCl ²⁺	-12.94	-22.12
FeCl ⁺	-15.16	-24.92
FeCl ^o	-19.60	-29.72

hydroxide is the iron mineral controlling concentrations of dissolved iron in oxic water, and assuming that Fe²⁺ is the predominant species, the following equation applies:



Forming the reaction quotient and setting the activities of H₂O and Fe(OH)₃ equal to unity:

$$K_e = \frac{[\text{H}^+]^2}{[\text{Fe}^{2+}] [\text{O}_2]^{1/4}} \quad (31)$$

solving for [Fe²⁺] and taking logs:

$$\log [\text{Fe}^{2+}] = 2 \log [\text{H}^+] - 1/4 \log [\text{O}_2] - \log K_e \quad (32)$$

or:

$$\log [\text{Fe}^{2+}] = -2\text{pH} - 1/4 \log [\text{O}_2] - \log K_e \quad (33)$$

Because the pH of oxic water in the Patuxent and Patapsco water varies from 4.5 to 6.5, equation 33 can be used to construct a stability diagram for this system. Figure 29a shows the concentrations of total dissolved iron from chemical analyses plotted as a function of dissolved oxygen. Figure 29a demonstrates that total iron concentrations are much higher than predicted by equation 33. This suggests that Fe²⁺ is not a major species in oxic water and that other dissolved iron species must be contributing to total dissolved iron. This, in turn, is consistent with the WATEQF speciation calculations for the water of well BA-Fe 51.

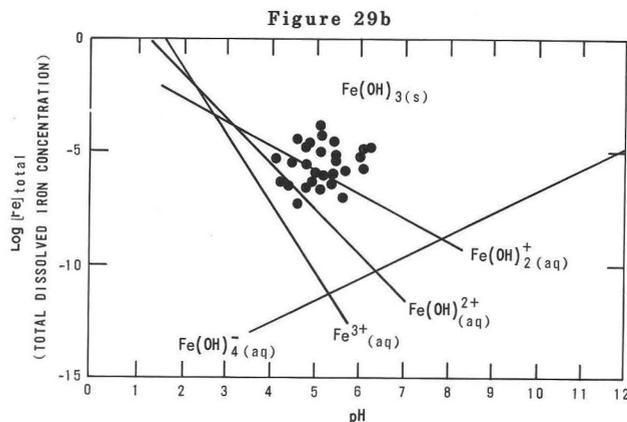
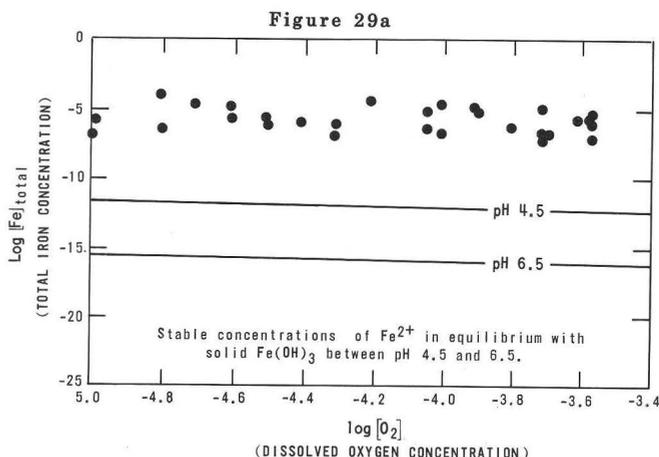


Figure 29.—Measured concentrations of total dissolved iron superimposed on stability diagrams for Fe²⁺ and several Fe³⁺ species in equilibrium with Fe(OH)₃.

The next step in this analysis is to set up a similar system, but, in this case, assume Fe(OH)₂⁺ is the predominant dissolved species. In this case, the equation:



applies. Again forming the reactions quotient, taking logs, and solving for $\log [\text{Fe(OH)}_2^+]$:

$$\log \text{Fe(OH)}_2^+ = -\text{pH} - \log K_e \quad (35)$$

$$\log K_e = +0.78$$

For completeness, the iron (III) species Fe^{3+} , Fe(OH)^{2+} , and Fe(OH)_4^- may be treated similarly:

$$\log [\text{Fe}^{3+}] = -3 \text{pH} + \log K_e \quad (36)$$

$$\log K_e = 4.885$$

$$\log [\text{Fe(OH)}^{2+}] = -2 \text{pH} - K_e \quad (37)$$

$$\log K_e = -2.70$$

$$\log [\text{Fe(OH)}_4^-] = \text{pH} - \log K_e \quad (38)$$

$$\log K_e = 16.71$$

Equations 35 through 38 can be used to construct a stability diagram for this system. Figure 29b shows this stability diagram and concentrations of total iron in oxic Patuxent and Patapsco aquifer water plotted as a function of pH. This figure shows that there is con-

siderable variability in concentrations of total dissolved iron. However, observed concentrations tend to scatter in the proximity of the $\text{Fe(OH)}_2^+ - \text{Fe(OH)}_3$ boundary. This suggests that observed concentrations of total iron can be nearly accounted for by assuming Fe(OH)_2^+ is the predominant species. Again, this demonstrates that the calculated speciation of iron by WATEQF (table 8) applies generally to oxic water in the Patuxent and Patapsco aquifers.

Water from the Patuxent aquifer near Baltimore commonly is treated to remove dissolved iron. The chemical speciation of iron, as demonstrated in table 8, has important implications for the types of treatment that are economically desirable. For example, because dissolved iron in zone 3a is predominantly in the oxidized state as Fe(OH)_2^+ , investing in expensive water-oxygenation equipment probably is not warranted. In this case, simply raising the pH of the water will decrease dissolved iron concentrations according to equation 35 (fig. 29b). In zone 3b, however, dissolved iron is present predominantly in the reduced state as Fe^{2+} , and water-oxygenation will be necessary to decrease iron concentrations according to equation 33 (fig. 29a). In view of the difference between iron speciation in zone 3a and 3b, it may be economically desirable to locate future municipal well fields in zone 3a.

SUMMARY AND CONCLUSIONS

The Patuxent Formation is a medium- to coarse-grained sand that exhibits lenses of gravel and silty clay. The Patuxent Formation was deposited in a fluvial environment. The lower part of the unit was deposited in a high-energy braided-stream environment. The upper parts of the unit were deposited under progressively lower energy conditions. As a result of the changing stream gradients, the Patuxent exhibits an overall fining-upward lithology. Superimposed on this overall fining-upward trend are sequences of small-scale (5–30 ft) fining-upward sequences and clay lenses. These small-scale sequences reflect channel shifts and cutoffs characteristic of fluvial sedimentation.

The Arundel Formation conformably overlies the Patuxent Formation. The Arundel Formation is a predominantly clay unit that was deposited in a low-energy, marshy environment.

The Patapsco Formation unconformably overlies the Arundel Formation. The Patapsco consists predominantly of fine- to medium-grained sand with lenses of clay and silty clay. Patapsco sedimentation records a

rejuvenation of stream gradients that occurred at the end of Aptian time.

The Patuxent Formation is extensively tapped as a source of ground water in the Baltimore area. In 1982, approximately 11 Mgal/d of water was produced from this unit. Transmissivities of this unit are on the order of 2,000–8,000 ft^2/d and tend to increase in the direction of dip. The Patuxent is confined by the overlying clays of the Arundel Formation. The Arundel serves as an extremely tight confining bed that exhibits hydraulic conductivities on the order of 10^{-9} to 10^{-11} ft/s. The Patapsco Formation serves as an aquifer in much of the Baltimore area. However, brackish water and other contamination problems experienced between 1930 and 1955 have greatly reduced pumpage from this unit. There are presently no large capacity well fields producing from the Patapsco aquifer in Baltimore City. The aquifer is used extensively, however, in northern Anne Arundel County. Throughout much of Baltimore, the Patapsco is under water-table conditions.

The Patuxent aquifer in the Baltimore industrial

area has been severely contaminated by brackish-water intrusion from the Patapsco River estuary. A circular plume of contamination, about 5 mi in diameter, has developed in response to heavy pumpage. This plume, which has chloride concentrations ranging from 100 to 5,000 mg/L, is centered in the Harbor district. Borehole data gathered during construction of the Fort McHenry tunnel demonstrate that the Arundel Formation has been incised by Pleistocene channels. These channels completely truncate the Arundel in the Harbor area. The more permeable sediments that presently fill these channels provide a conduit for brackish water to leak into the Patuxent aquifer.

A two-dimensional areal solute-transport model of the Patuxent aquifer near Baltimore was constructed. The model was designed at a relatively large scale to simulate the behavior of the contamination plume. The model was calibrated in two steps. First, leakance values of the overlying confining bed (the Arundel Formation) were adjusted so that the model could reproduce the water-level history of the aquifer. Once the flow model was calibrated, aquifer dispersivity was adjusted until the simulated position of the contaminated plume matched the observed position.

Once calibrated, the model was used to simulate the future behavior of the plume based on alternative scenarios of aquifer use. The simulations included:

- (1) A simulation of future chloride movement that assumes the 1982 pumping patterns continue for 50 years. This simulation predicts that very little movement of the plume will result from the specified conditions. This suggests that the plume currently has stabilized with respect to present patterns and rates of pumpage.
- (2) A simulation of chloride movement that doubles the 1982 Sparrows Point pumpage and keeps all other pumpage at 1982 rates. This simulation predicts that the chloride plume will shift toward Sparrows Point between 1/2 and 1 mi over a 50-year period. On the basis of this simulation, it appears unlikely that the plume will reach Sparrows Point in the foreseeable future, even if pumpage there is increased.
- (3) A simulation of chloride movement that assumes all pumpage ceases after 1982. This simulation predicts that the area of chloride contamination would continue to increase slightly. This, in turn, suggests that stopping pumpage would not contribute substantially to reducing the chloride contamination problem.

- (4) A simulation that assumes a 100-ft cone of depression exists at the Glen Burnie well fields in Anne Arundel County. This simulation was designed to see if the plume may be drawn toward Glen Burnie if water levels there drop significantly. A slight shift toward Glen Burnie was noted in the simulation results. This shift is not large or fast enough to conclude that the Glen Burnie well field might become contaminated in the foreseeable future.
- (5) A simulation of 5-Mgal/d pumpage in Marley Neck, Anne Arundel County. In this 50-year simulation, a cone of depression about 60 ft below sea level is predicted to develop. The chloride contamination plume also shifts very close to the simulated pumping center. This suggests that prolonged pumpage in Marley Neck may induce future chloride contamination.
- (6) A simulation of 5-Mgal/d pumpage in Marley Neck with a line of four fresh-water injection wells between the pumping center and the chloride plume. In this 50-year simulation, each recharge well injected 1 Mgal/d of fresh-water. The rate of chloride movement toward the pumping center was much less than the non-recharge scenario of simulation 5. Additional simulations demonstrate that recharge rates of 10,000 gal/d per well do not significantly impede chloride movement.

The most important conclusion that can be drawn from the six simulations is that future movement of the chloride plume probably will be very slow. This is in sharp contrast to the plume's behavior in the recent past when it grew and spread very rapidly. It is also unlikely that the plume will spread to pumping centers in Sparrows Point or Glen Burnie in the foreseeable future. It is unlikely that simply stopping all pumpage in the Baltimore area will result in any significant improvement in water quality. It is, however, possible that significant pumping stress in the Marley Neck area of Anne Arundel County could cause the plume to migrate toward that pumping center. Fresh-water recharge wells may impede the plume's movement, but very high recharge rates are necessary to achieve this effect.

Three water-quality zones are recognized in the Patuxent aquifer: *Zone 1*—This zone corresponds to the plume of brackish-water contamination. *Zone 2*—This zone exhibits evidence of urbanization-related contamination such as elevated concentrations of total organic carbon and chlorides from road salts. Measurable concentrations of organic chemicals such as benzene, trichloroethylene, and toluene are also ob-

served. Concentrations of chromium, copper, zinc, and cadmium may be from 2 to 10 times higher than in the other zones. *Zone 3*—This zone contains water that is uncontaminated. Water quality is controlled exclusively by natural chemical processes.

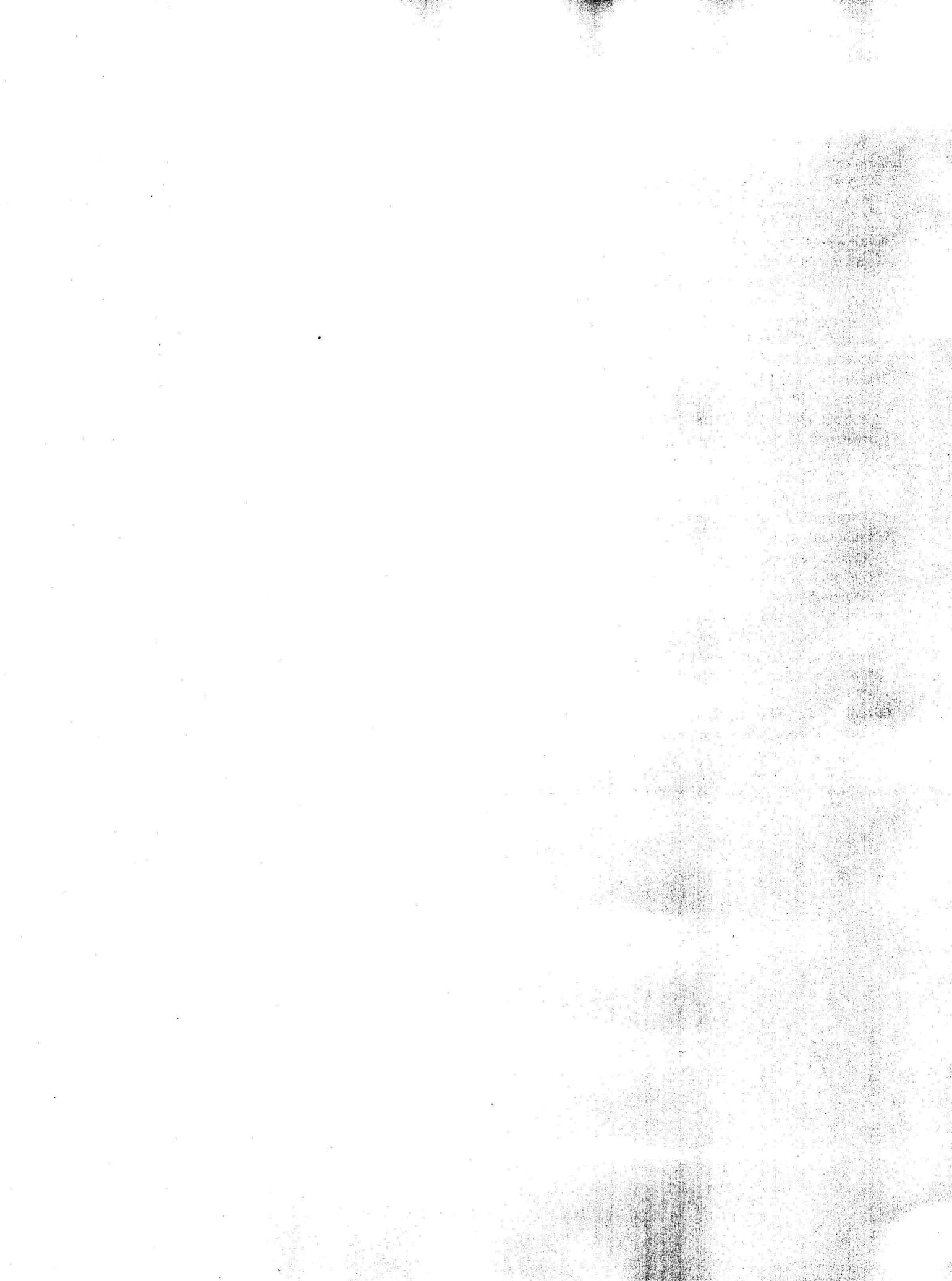
Uncontaminated water in the Patuxent aquifer (zone 3) changes composition as it moves along the hydrologic gradient. Near the outcrop area, the water contains measurable concentrations of dissolved oxygen

and low concentrations of dissolved iron and sulfate. Dissolved oxygen is consumed along the flowpath by oxidation of pyrite and lignite and by precipitation of secondary iron hydroxide cementation. The predominant dissolved iron species in oxic water is $\text{Fe}(\text{OH})_2^+$. Downgradient water is anoxic and contains higher dissolved iron concentrations and measurable concentrations of hydrogen sulfide. The predominant dissolved iron species in anoxic water is Fe^{2+} .

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WELL RECORDS, PUMPAGE INFORMATION, AND OTHER SUPPLEMENTAL DATA

Compiled by
Tracey M. Kean

Table 9.—Records of selected wells in the Baltimore area

USGS Well No.	State Permit No.	Owner	Driller	Completion year	Method of drilling	Altitude of land surface (feet)	Diameter of casing at lsd (inches)	Total depth drilled (feet)	Depth of casing (feet)	Screen intervals (feet below land surface)	Screen diameter (inches)	Finish
Ac 68	AA-74-2173	Clark, George	H.H. Bunker & Sons, Inc.	1980	H	170	4	115	110	108-115	2	G
Ac 69	AA-73-3375	Jones, Samuel	Branham Contractors, Inc.	1974	H	160	4	230	223	223-230	2	G
Ac 70	AA-74-2909	Rolnicki, R.	Frank's Well Drill., Inc.	1981	H	135	4	173	163	163-173	2	G
Ad 41	AA-00-1630	A.A. County Dept. Pub. Works	Layne-Atlantic Co.	1947	H	39	18	153	126	126-146	8	G
Ad 60	AA-01-9426	J. J. Hock, Inc.	Maryland Drill. Co.	1955	H	15	4	68	68	48-52	4	S
Ad 74	AA-02-8580	A.A. County Dept. Pub. Works	Layne-Atlantic Co.	1957	H	90	12	186	171	171-186	10	S
Ad 76	AA-02-9134	A.A. County Dept. Pub. Works	Layne-Atlantic Co.	1957	H	75	12	474	449	449-474	10	S
Ad 94	AA-02-6010	Matlack, Inc.	Sam Shannahan Well Co.	1957	H	38	6	214	198	198-213	4	S
Ad 98	AA-73-7847	Amerada Hess Corp.	Frank's Well Drill., Inc.	1977	H	92	8	310	295	295-310	8	G
Ad 99	AA-73-4665	U.S.S. Agri-Chemicals Div.	Frank's Well Drill., Inc.	1975	H	12	6	371	361	361-371	4	G
Ad 100	AA-73-3825	J. J. Hock Inc.	Frank's Well Drill., Inc.	1975	H	15	6	275	265	265-275	4	G
Ad 101	AA-74-1856	A.A. County Reclamation Area	H.H. Bunker & Sons, Inc.	1980	H	10	4	32	17	17-32	4	G
Ae 36	AA-04-6091	Chemetals Inc.	Shannahan Artesian Well Co.	1962	H	30	16	567	532	450-500 532-555	8	S
Ae 37	AA-73-5969	Solley United Meth. Ch.	Frank's Well Drill., Inc.	1976	H	55	4	101	96	96-101	2	G
Bb 77	AA-73-6150	Max Blob's Park	Frank's Well Drill., Inc.	1976	H	180	6	145	140	140-145	4	G
Bb 78	AA-72-0819	Fields, Edward	Frank's Well Drill., Inc.	1972	H	300	4	223	218	218-223	2	G
Bb 79	AA-74-0854	A.A. County Dept. Gen. Services	C-Z Enterprises	1979	H	130	12	113	75	75-85	12	G
Be 205	AA-73-6389	Davco Food Corp. (Wendy's)	H.H. Bunker & Sons, Inc.	1977	H	160	4	90	85	85-90	2	G
Be 206	AA-74-1126	Griffin, P.	Slater's Well Drilling Co.	1979	H	120	4	110	100	100-107	2	G
Be 207	AA-73-3892	Hanover Assembly of God	Branham Contractors, Inc.	1974	H	205	4	180	170	170-180	2	G

Drilling codes

D = Dug
H = Drilled

Finish Codes

C = Concrete rings
G = Gravel pack & screen
O = Open hole
S = Screen

Principal aquifer	Static water level (feet below land surface)	Date	Use	Pump	Yield (gal/min)	Duration of test (hours)	Draw-down (feet)	Specific capacity	Date	Remarks	USGS Well No.
Anne Arundel County											
Patapsco	80.39	03-30 1982	D	S	10	1	18	0.6	07-25 1980	D	Ac 68
Patuxent	128.43	03-29 1982	D	S	15	3	25	0.6	08-07 1974	D	Ac 69
Patuxent	145.70	10-19 1981	D	S	10	2	10	1.0	03-17 1981	D	Ac 70
Patapsco	32.15	04-15 1982	P	T	250	-	58	4.3	06-04 1947	D,A; Sawmill Creek well 5.	Ad 41
Patapsco	11.76	08-11 1981	U	J	25	-	21	1.2	09-02 1955	D	Ad 60
Patapsco	50.63	04-01 1982	P	T	375	8	124	3.0	00-00 1957	D,A; Dorsey Road well 4.	Ad 74
Patuxent	112.79	04-15 1982	P	T	450	8	135	3.3	11-15 1957	D,A; Dorsey Road well 5.	Ad 76
Patuxent	26.00	03-29 1982	N	S	75	10	31	2.4	05-28 1957	D	Ad 94
Patuxent	94.10	03-29 1982	U,O	-	125	4	40	3.1	11-22 1977	D	Ad 98
Patuxent	20.00	07-25 1975	N	S	250	3	15	16.7	07-25 1975	D,A	Ad 99
Patuxent	12.99	03-29 1982	C	S	100	5	54	1.9	01-21 1975	D	Ad 100
Patapsco	8.30	08-04 1981	O	-	15	1	4	3.8	05-16 1980	D	Ad 101
Patuxent	36.00	04-19 1982	N	T	740	24	40	18.5	04-19 1982	D,A	Ae 36
Patapsco	36.72	03-30 1982	T	S	18	2	10	1.8	05-28 1976	D	Ae 37
Patuxent	105.32	03-29 1982	C	S	50	3	10	5.0	07-16 1976	D	Bb 77
Patuxent	180.17	03-29 1982	D	S	8	1	10	0.8	02-28 1972	D	Bb 78
Patapsco	F	07-29 1981	U	-	100	24	74	1.4	12-00 1979	D; flowing well.	Bb 79
Patapsco	42.31	03-30 1982	C	S	20	2	20	1.0	02-04 1977	D	Be 205
Patuxent	42.75	07-31 1981	D	S	15	4	10	1.5	11-18 1979	D	Be 206
Patuxent	103.02	03-29 1982	T	S	20	3	20	1.0	12-02 1974	D	Be 207

Usage

C = Commercial
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N = Industrial
O = Observation
P = Public supply
R = Recreational
S = Stock
T = Institutional
U = Unused
Z = Other

Pump type

J = Jet
O = Other
S = Submersible
T = Turbine

Remarks

A = Chemical analysis
C = Caliper log
D = Descriptive log
E = Electric logs
G = Gamma log
O = Other logs

Table 9.—Records of selected wells in the Baltimore area—Continued

USGS Well No.	State Permit No.	Owner	Driller	Completion year	Method of drilling	Altitude of land surface (feet)	Diameter of casing at lsd (inches)	Total depth drilled (feet)	Depth of casing (feet)	Screen intervals (feet below land surface)	Screen diameter (inches)	Finish
Anne Arundel County (cont.)												
Bc 208	AA-73-3460	O'Toole, Bonnie	H.J. Greer Drill., Inc.	1974	H	130	4	75	70	70-75	2	S
Bd 64	AA-02-8059	A.A. County Dept. Pub. Works	Layne-Atlantic Co.	1957	H	73	12	181	161	161-181	10	S
Bd 66	AA-02-8416	A.A. County Dept. Pub. Works	Layne-Atlantic Co.	1957	H	85	12	517	497	497-517	10	S
Bd 92	AA-04-2472	A.A. County Dept. Pub. Works	Layne-Atlantic Co.	1961	H	85	10	157	132	132-157	10	S
Bd 95	AA-05-0489	A.A. County Dept. Pub. Works	Layne-Atlantic Co.	1963	H	70	10	178	150	150-160 168-178	10	S
Bd 97	AA-04-9554	A.A. County Dept. Pub. Works	Layne-Atlantic Co.	1962	H	75	10	548	504	504-534	10	S
Bd 98	AA-05-7226	A.A. County Dept. Pub. Works	Layne-Atlantic Co.	1964	H	75	10	625	552	552-591	10	S
Bd 117	AA-71-1083	Briscoe, J.	Frank's Well Drill., Inc.	1971	H	45	4	200	195	195-200	2	G
Bd 118	AA-73-4962	Neidert, William, Sr.	Branham Contractors, Inc.	1975	H	150	4	185	178	178-185	2	G
Bd 119	AA-74-1244	Whitlock, D. A.	Branham Contractors, Inc.	1979	H	140	4	188	181	181-188	2	G
Bd 120	AA-72-0346	British Petroleum Gas Station	Frank's Well Drill., Inc.	1971	H	85	4	170	165	165-170	2	G
Be 106	AA-72-0100	Weigman, J.	V. Ernsberger	1971	H	25	4	130	120	120-130	3	G
Be 107	AA-74-0822	Pasadena Body & Auto Shop	D. Wolford	1979	H	90	4	172	165	165-172	4	G
Bf 51	AA-70-0392	Bodkin Elem. School	Layne-Atlantic Co.	1969	H	45	12	179	147	147-167	6	G

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Finish codes

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Principal aquifer	Static water level (feet below land surface)	Date	Use	Pump	Yield (gal/min)	Duration of test (hours)	Draw-down (feet)	Specific capacity	Date	Remarks	USGS Well No.
Anne Arundel County (cont.)											
Patapsco	35.12	08-04 1981	D	S	15	1	8	1.9	09-14 1974	D	Bc 208
Patapsco	13.00	09-12 1957	P	T	375	8	157	2.4	09-12 1957	D,A; Dorsey Road well 11.	Bd 64
Patuxent	31.00	10-31 1957	P	T	375	8	183	2.0	10-31 1957	A; Dorsey Road well 13.	Bd 66
Patapsco	22.00	05-31 1961	P	T	200	24	98	2.0	05-31 1961	D,E,A; Dorsey Road well 14.	Bd 92
Patapsco	19.00	02-21 1963	P	T	350	24	123	2.8	02-21 1963	D,A; Dorsey Road well 15.	Bd 95
Patuxent	26.00	11-05 1962	P	T	500	40	121	4.1	11-06 1962	D,A; Dorsey Road well 16.	Bd 97
Patuxent	108.55	04-01 1982	P	T	907	8	147	6.2	08-03 1964	D,E,G,A; Dorsey Road well 17.	Bd 98
Patapsco	43.17	10-14 1981	D	S	30	1	10	3.0	08-17 1971	D	Bd 117
Patapsco	101.10	03-30 1982	D	S	10	3	30	0.3	09-12 1975	D	Bd 118
Patapsco	93.28	10-14 1981	D	S	35	2	20	1.8	10-02 1979	D	Bd 119
Patapsco	60.14	03-30 1982	C	S	25	1	10	2.5	10-22 1971	D	Bd 120
Patapsco	22.90	08-22 1981	D	S	20	1.5	-	-	08-20 1971	D	Be 106
Patapsco	80.42	03-29 1982	C	S	15	1	97	0.2	07-23 1979	D	Be 107
Patapsco	37.42	03-29 1982	T	T	130	12	41	3.2	12-15 1969	D	Bf 51

Usage

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 N = Industrial
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 P = Public supply
 R = Recreational
 S = Stock
 T = Institutional
 U = Unused
 Z = Other

Pump type

 J = Jet
 O = Other
 S = Submersible
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Remarks

 A = Chemical analysis
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Table 9.—Records of selected wells in the Baltimore area—Continued

USGS Well No.	State Permit No.	Owner	Driller	Completion year	Method of drilling	Altitude of land surface (feet)	Diameter of casing at lsd (inches)	Total depth drilled (feet)	Depth of casing (feet)	Screen intervals (feet below land surface)	Screen diameter (inches)	Finish
Baltimore City												
1N3E 9	BC-69-0001	Hood Vinegar Co.	C.Trifillis	1968	H	110	6	155	-	-	-	G
1N3E 10	BC-71-0001	Hood Vinegar Co.	Frank's Well Drill., Inc.	1971	H	100	6	100	90	90-100	4	G
1N3E 11	BC-70-0003	Hood Vinegar Co.	Frank's Well Drill., Inc.	1970	H	100	6	105	90	90-100	-	G
1N5E 3	BC-73-0001	Dur-O-Wal Products, Inc.	Frank's Well Drill., Inc.	1974	H	20	4	110	105	105-110	2	G
1N5E 4	BC-73-0002	Dur-O-Wal Products, Inc.	Frank's Well Drill., Inc.	1974	H	20	4	115	110	110-115	2	G
1S1W 35	BC-04-4248	Civic Center	Maryland Drill. Co.	1961	H	50	6	182	65	-	-	O
1S1W 36	BC-73-0078	Federal Reserve Bank	Frank's Well Drill., Inc.	1982	H	30	6	350	8	84-350	-	-
1S3E 45	BC-67-0001	Schluderberg-Kurdle Co., Inc.	Shannahan Artesian Well Co.	1967	H	70	10	185	160	160-185	10	S
1S3E 46	BC-71-0003	Schluderberg-Kurdle Co., Inc.	Shannahan Artesian Well Co.	1971	H	70	10	210	159	159-173 185-198	10	G
1S3E 47	BC-73-0029	Schluderberg-Kurdle Co., Inc.	C-Z Enterprises	1980	H	55	8	173	140	140-160	8	G
1S3E 48	BC-66-0002	U-Haul Co.	Layne-Atlantic Co.	1966	H	60	8	167	140	140-155	8	S
2S5E 1	-	Ft. Holabird Industrial Pk.	Virginia Mach. & Well Co.	1930	H	32	12	290	-	-	-	S
3S2E 5	BC-81-0087	USGS (Latrobe Park)	East Coast Well & Pump Co.	1982	H	15	4	185	137	137-147	3	G
3S3E 36	BC-73-0040	Balto. City (Lazaretto Pt.)	Frank's Well Drill., Inc.	1981	H	16	4	230	225	225-230	3	G
3S3E 37	BC-73-0039	Balto. City (Lazaretto Pt.)	Frank's Well Drill., Inc.	1981	H	9	6	149	129	129-149	3	G
3S3E 38	BC-73-0042	Balto. City (Lazaretto Pt.)	Frank's Well Drill., Inc.	1981	H	16	4	114	109	109-114	3	G
3S3E 39	BC-73-0041	Balto. City (Lazaretto Pt.)	Frank's Well Drill., Inc.	1981	H	16	4	147	142	142-147	3	G
3S3E 40	BC-73-0043	Balto. City (Lazaretto Pt.)	Frank's Well Drill., Inc.	1981	H	16	4	20	15	15-20	3	G
3S4E 15	BC-73-0019	Balto. Gas & Electric Co.	Frank's Well Drill., Inc.	1979	H	20	4	285	190	190-260	4	G

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Principal aquifer	Static water level (feet below land surface)	Date	Use	Pump	Yield (gal/min)	Duration of test (hours)	Draw-down (feet)	Specific capacity	Date	Remarks	USGS Well No.
Baltimore City											
Patuxent	65.32	03-29 1982	N	S	-	-	-	-	-	D,G,A; owner's well 1.	1N3E 9
Patuxent	75.00	05-14 1971	N	S	60	2	15	4.0	05-14 1971	D; owner's well 2.	1N3E 10
Patuxent	80.00	05-07 1970	N	S	22	2	10	2.2	05-07 1970	D,A; owner's well 3.	1N3E 11
Patuxent	22.00	06-03 1974	Z	-	175	2	15	11.7	06-03 1974	D; injection well.	1N5E 3
Patuxent	23.36	08-10 1981	N	S	75	1	15	5.0	06-03 1974	D,A	1N5E 4
Basement complex	33.51	03-30 1982	U	S	4	-	-	-	08-00 1961	D,A	1S1W 35
Basement complex	34.64	03-30 1982	U	-	20	24	111	0.2	02-01 1982	D	1S1W 36
Patuxent	97.00	05-05 1967	N	T	300	24	39	7.7	05-06 1967	D; owner's well 20.	1S3E 45
Patuxent	105.00	03-23 1971	N	T	182	8	48	3.8	03-23 1971	D,A; owner's well 22.	1S3E 46
Patuxent	77.34	03-30 1982	N	T	70	24	69	1.0	06-17 1980	D; owner's well 24.	1S3E 47
Patuxent	66.80	03-29 1982	U	T	150	16	63	2.4	05-04 1966	D; formerly Jos. E. Seagram & Sons.	1S3E 48
Patuxent	55.52	03-29 1982	O	-	260	0.25	21	12.4	00-00 1941	USGS observation well.	2S5E 1
Patuxent	17.17	01-03 1983	O	-	25	4	6	4.2	10-26 1982	D,E,G,C,O,A; USGS observation well.	3S2E 5
Patuxent	24.47	03-02 1981	O	-	10	-	-	-	-	D,E,G,C,A	3S3E 36
Patuxent	15.52	03-10 1981	O	-	10	-	-	-	-	D,E,G	3S3E 37
Patuxent	20.69	03-02 1981	O	-	270	-	-	-	-	D,A	3S3E 38
Patuxent	20.58	03-02 1981	O	-	10	-	-	-	-	-	3S3E 39
Pleisto.	5.15	03-02 1981	O	-	2	-	-	-	-	-	3S3E 40
Patuxent	34.45	09-17 1981	Z	-	10	2	10	1.0	10-11 1979	D,A	3S4E 15

Usage

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Pump type

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Table 9.—Records of selected wells in the Baltimore area—Continued

USGS Well No.	State Permit No.	Owner	Driller	Completion year	Method of drilling	Altitude of land surface (feet)	Diameter of casing at lsd (inches)	Total depth drilled (feet)	Depth of casing (feet)	Screen intervals (feet below land surface)	Screen diameter (inches)	Finish
3S4E 16	BC-73 -0020	Balto. Gas & Electric Co.	Frank's Well Drill., Inc.	1979	H	20	4	310	180	180-250	4	G
3S5E 35	BC-69 -0003	Federal Yeast Co.	Shannahan Artesian Well Co.	1969	H	15	12	387	270	270-300 350-370	8	S
3S5E 39	BC-68 -0002	Federal Yeast Co.	Shannahan Artesian Well Co.	1968	H	15	12	391	281	281-303 313-332 367-391	8	S
3S5E 40	BC-70 -0002	Federal Yeast Co.	Shannahan Artesian Well Co.	1971	H	15	12	397	296	291-312 319-335 361-396	8	S
3S5E 41	BC-71 -0002	Federal Yeast Co.	Shannahan Artesian Well Co.	1971	H	15	12	396	272	267-303 355-396	8	G
3E5E 42	BC-73 -0004	Federal Yeast Co.	Shannahan Artesian Well Co.	1975	H	15	12	404	286	284-314 367-375 375-400	8	S
3S5E 43	BC-73 -0012	Federal Yeast Co.	Shannahan Artesian Well Co.	1976	H	15	12	400	292	290-316 347-362 372-389	8	G
3S5E 44	BC-73 -0021	Balto. Gas & Electric Co.	Frank's Well Drill., Inc.	1979	H	15	4	340	260	260-320	4	G
3S5E 45	BC-81 -0068	Federal Yeast Co.	Shannahan Artesian Well Co.	1982	H	15	12	413	388	268-341 361-388	8	S
3S5E 46	BC-81 -0088	USGS (Colgate Creek)	East Coast Well & Pump Co.	1982	H	5	4	71	50	40-50	3	G
5S2E 20	-	FMC Corp.	Shannahan Artesian Well Co.	1946	H	5	10	300	222	222-262	-	S
5S2E 22	BC-03 -8814	FMC Corp.	Shannahan Artesian Well Co.	1960	H	5	10	260	220	219-257	10	S
5S2E 23	BC-01 -8470	Poe, Ben	Layne-Atlantic Co.	1955	H	43	4	80	74	75-80	2	S
5S2E 24	BC-81 -0089	USGS (Farring Park 1)	East Coast Well & Pump Co.	1982	H	75	4	270	260	260-270	3	G
5S2E 25	BC-81 -0090	USGS (Farring Park 2)	East Coast Pump & Well Co.	1982	H	75	4	115	105	105-115	3	G
7S4E	BC-01 -7129	SCM Corp.	Shannahan Artesian Well Co.	1954	H	40	2	638	565	565-575	2	S
7S4E 2	BC-73 -0038	Allied Chemical Corp.	D. Wolford	1980	H	23	4	118	111	111-118	-	-

Drilling codes

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Finish codes

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Principal aquifer	Static water level (feet below land surface)	Date	Use	Pump	Yield (gal/min)	Duration of test (hours)	Draw down (feet)	Specific capacity	Date	Remarks	USGS Well No.
Baltimore City (cont.)											
Patuxent	46.28	09-17 1981	Z	-	10	4	10	1.0	03-07 1979	D	3S4E 16
Patuxent	61.00	05-23 1969	N	T	106	12	6	17.7	05-23 1969	D,A	3S5E 35
Patuxent	62.00	06-28 1968	N	T	650	32	93	7.0	06-28 1968	D,A	3S5E 39
Patuxent	65.00	04-26 1971	N	T	680	24	37	18.4	04-27 1971	D,A	3S5E 40
Patuxent	62.00	07-03 1971	N	T	620	24	31	20.0	07-04 1971	D,A	3S5E 41
Patuxent	65.00	00-00 1975	N	T	750	8	70	10.7	00-00 1975	D,A	3S5E 42
Patuxent	60.00	04-20 1976	N	T	350	8	50	7.0	04-20 1976	D,A	3S5E 43
Patuxent	42.93	09-18 1981	Z	-	10	2	10	1.0	11-05 1979	D,A	3S5E 44
Patuxent	65.00	11-02 1982	N	T	566	-	35	16.2	11-02 1982	D	3S5E 45
Patapsco	1.52	01-03 1983	O	-	5	4	59	0.1	10-20 1982	D,E,G,C,O; USGS obser- vation well.	3S5E 46
Patuxent	7.55	03-31 1982	U	T	310	-	32	9.7	00-00 1946	D,E,A	5S2E 20
Patuxent	7.12	03-31 1982	U	T	465	4	51	9.0	06-30 1960	D	5S2E 22
Patapsco	34.00	04-06 1955	U	S	50	3	7	7.1	04-06 1955	D,A	5S2E 23
Patuxent	63.89	01-03 1983	O	-	8	4	194	0.04	10-29 1982	D,G,A; USGS observation well.	5S2E 24
Patapsco	45.89	01-03 1983	O	-	5	4	56	0.1	11-02 1982	D,G,A; USGS observation well.	5S2E 25
Patuxent	60.07	04-23 1982	U,O	-	8	4	-	-	10-30 1954	D; USGS observation well.	7S4E 1
Patapsco	19.74	03-31 1982	D	-	-	-	-	-	-	D,A	7S4E 2

Usage

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Pump type

 J = Jet
 O = Other
 S = Submersible
 T = Turbine

Remarks

 A = Chemical analysis
 C = Caliper log
 D = Descriptive log
 E = Electric logs
 G = Gamma log
 O = Other logs

Table 9.--Records of selected wells in the Baltimore area--Continued

USGS Well No.	State Permit No.	Owner	Driller	Completion year	Method of drilling	Altitude of land surface (feet)	Diameter of casing at lsd (inches)	Total depth drilled (feet)	Depth of casing (feet)	Screen intervals (feet below land surface)	Screen diameter (inches)	Finish
Baltimore County												
Ef 261	BA-73-6346	Richardson's Chicken Farm	Frank's Well Drill., Inc.	1979	H	80	4	123	118	118-123	2	G
Ef 263	BA-71-0296	Dansberger Florists	W.H. Eiler	1971	H	155	4	60	55	55-60	2	G
Ef 264	BA-67-0084	Baker, A.	H. S. Rawle	1966	D	115	36	26	-	-	-	C
Ef 265	-	Dodson Trucking Co.	-	-	H	65	12	22	-	-	-	-
Eg 142	BA-65-0496	Ebenezer United Methodist Church	W.H. Eiler	1965	H	70	4	140	135	135-140	-	S
Eg 146	BA-73-7660	Gunpowder Neck St. Park	Frank's Well Drill., Inc.	1980	H	5	6	285	200	200-210	6	G
Eg 147	-	Gunpowder Neck St. Park	-	-	D	5	36	40	-	-	36	C
Eg 148	BA-73-2130	Thompson, H.	W. Leonard	1975	H	10	4	70	65	63-70	2	G
Eg 149	BA-73-0464	Steiner, R.	W. Leonard	1972	H	15	4	50	45	43-50	2	G
Eg 150	BA-73-1990	Marshy Pt. Nursery	W. Leonard	1975	H	5	6	255	245	245-255	6	G
Eg 151	BA-73-1192	Marshy Pt. Nursery	W. Leonard	1974	H	20	4	185	179	179-185	-	G
Eg 152	-	Marshy Pt. Nursery	-	-	D	10	36	25	-	-	-	C
Eg 153	BA-73-3177	Myers, J.	W. Leonard	1976	H	15	4	125	120	120-125	2	G
Eg 154	BA-81-0618	Balto. Co. (Eastern Sanitary Landfill)	L. F. Easterday, Inc.	1982	H	62	4	109	94	94-104	4	G
Fc 51	BA-73-0292	W.R.B.S. Radio Station	G. Edgar Harr Sons' Corp.	1972	H	220	6	180	180	-	-	O
Fc 52	BA-73-0860	Heinzerling, L.	Frank's Well Drill., Inc.	1973	H	190	4	125	115	115-125	2	G
Fc 19	-	Jos. E. Seagram & Sons	G. Edgar Harr Sons' Corp.	1936	H	35	8	402	-	-	-	S
Fc 59	BA-67-0369	Eastern Stainless Steel Co.	Shannahan Artesian Well Co.	1967	H	40	-	320	291	291-320	-	S

Drilling codes

D = Dug
H = Drilled

Finish codes

C = Concrete rings
G = Gravel pack & screen
O = Open hole
S = Screen

Principal aquifer	Static Water level (feet below land surface)	Date	Use	Pump	Yield (gal/min)	Duration of test (hours)	Draw-down (feet)	Specific capacity	Date	Remarks	USGS Well No.
Baltimore County											
Patuxent	63.42	03-30 1982	Z	S	25	2	10	2.5	01-23 1979	D	Ef 261
Patuxent	30.74	09-08 1981	U	J	5	8	5	1.0	03-06 1971	D	Ef 263
Patuxent	8.95	03-30 1982	U	-	-	-	-	-	-	D	Ef 264
Patapsco	9.48	03-30 1981	C	-	-	-	-	-	-	-	Ef 265
Patapsco	63.80	04-01 1982	T,D	S	10	4	18	0.6	02-19 1965	D	Eg 142
Patapsco	1.80	03-30 1982	R	S	30	24	8	3.8	10-28 1980	D	Eg 146
Patapsco	5.10	03-30 1982	D	S	-	-	-	-	-	-	Eg 147
Patapsco	12.48	03-30 1982	D	S	25	2	37	0.7	06-06 1975	D	Eg 148
Patapsco	18.89	08-10 1981	D	S	15	1	15	1.0	02-26 1972	D	Eg 149
Patuxent	1.31	03-30 1982	I	S	200	10	98	2.0	05-07 1975	D,A	Eg 150
Patapsco	16.19	03-30 1982	D	S	20	3	24	0.8	03-19 1974	D	Eg 151
Patapsco	11.62	03-29 1982	D	S	-	-	-	-	-	-	Eg 152
Patapsco	7.25	03-30 1982	D	S	40	-	8	5.0	06-17 1976	D	Eg 153
Patuxent	44.50	08-24 1982	O	-	-	-	-	-	-	D,A	Eg 154
Patuxent	127.22	04-28 1982	C	-	-	-	-	-	-	D,A	Fc 51
Patuxent	87.99	04-01 1982	D	S	20	2	10	2.0	07-07 1973	D	Fc 52
Patuxent	63.07	07-22 1982	U,O	-	250	-	-	-	00-00 1936	G; USGS observation well.	Fe 19
Patuxent	80.00	01-08 1967	N	T	-	-	-	-	-	D,E,A; owners well 18.	Fe 59

Usage codes

C = Commercial
D = Domestic
I = Irrigation
N = Industrial
O = Observation
P = Public supply
R = Recreational
S = Stock
T = Institutional
U = Unused
Z = Other

Pump type

J = Jet
O = Other
S = Submersible
O = Other

Remarks

A = Chemical analysis
C = Caliper log
D = Descriptive log
E = Electric logs
G = Gamma log
O = Other logs

Table 9.—Records of selected wells in the Baltimore area—Continued

USGS Well No.	State Permit No.	Owner	Driller	Completion year	Method of drilling	Altitude of land surface (feet)	Diameter of casing at 1st (inches)	Total depth drilled (feet)	Depth of casing (feet)	Screen intervals (feet below land surface)	Screen diameter (inches)	Finish
Fe 64	BA-73-3000	Eastern Stainless Steel Co.	Shannahan Artesian Well Co.	1976	H	45	10	325	271	271-307	10	G
Fe 66	BA-73-3002	Eastern Stainless Steel Co.	Shannahan Artesian Well Co.	1976	H	40	10	303	214	214-219 261-286 292-303	8	G
Fe 68	BA-73-6533	Jos. S. Merritt Florists	Frank's Well Drill., Inc.	1979	H	20	6	185	170	170-185	4	G
Fe 69	BC-00-5896	Jos. E. Seagram & Sons	Shannahan Artesian Well Co.	1950	H	50	10	492	-	395-412 455-476	-	G
Fe 70	BC-00-5896	Jos. E. Seagram & Sons	Shannahan Artesian Well Co.	1950	H	55	10	513	372	371-391 474-496	-	G
Ff 34	-	Back River Elementary School	-	1943	H	25	8	341	332	331-341	6	S
Ff 54	BA-01-4708	Salvo Auto Parts	Maryland Drill. Co.	1954	H	30	6	415	114	92-102	4	G
Ff 81	BA-03-1989	National Wire Prod. Corp.	W.H. Eiler	1958	H	15	4	94	89	89-94	4	S
Ff 85	BA-69-0373	American Yeast Corp.	Shannahan Artesian Well Co.	1969	H	22	12	615	-	438-477 559-585	6	S
Ff 86	BA-73-5195	Williams, Michael	Frank's Well Drill., Inc.	1978	H	10	4	60	55	53-60	2	G
Ff 87	BA-73-7186	Pivonski, Gary	W. Leonard	1979	H	15	4	180	175	175-180	2	G
Ff 88	BA-73-6117	Dickerson, Arthur R.	Frank's Well Drill., Inc.	1978	H	10	4	105	100	100-105	2	G
Ff 89	BA-73-3429	Rocky Pt. County Pk.	Frank's Well Drill., Inc.	1976	H	35	6	30	25	25-30	4	G
Fg 69	BA-70-0507	Rocky Pt. County Pk.	Shannahan Artesian Well Co.	1970	H	15	10	795	737	737-788	8	G
Fg 70	BA-73-6256	Rocky Pt. County Pk.	Frank's Well Drill., Inc.	1978	H	15	6	107	102	102-107	4	G
Fg 71	BA-73-7315	Kowaleski, Richard	Frank's Well Drill., Inc.	1980	H	5	4	62	52	52-62	2	G
Fg 72	BA-73-1527	Rocky Pt. County Pk.	W.H. Eiler	1974	H	15	6	26	22	21-26	2	G
Fg 73	BA-73-1084	Bury, Frank	W.H. Eiler	1973	H	20	4	253	248	248-253	2	G

Drilling codes

D = Dug
H = Drilled

Finish codes

C = Concrete rings
G = Gravel pack & screen
O = Open hole
S = Screen

Principal aquifer	Static water level (feet below land surface)	Date	Use	Pump	Yield (gal/min)	Duration of test (hours)	Draw-down (feet)	Specific capacity	Date	Remarks	USGS Well No.
Baltimore County (cont.)											
Patuxent	96.13	03-30 1982	N	T	430	8	46	9.3	08-27 1976	D,A; owner's well 19.	Fe 64
Patuxent	88.00	10-19 1976	N	T	435	8	88	4.9	10-19 1976	D,A; owner's well 20.	Fe 66
Patapsco	42.10	03-29 1982	I	S	150	45	88	1.7	05-07 1979	D,A	Fe 68
Patuxent	71.50	07-07 1982	N	T	405	24	86	4.7	07-19 1950	D,A; BA-Fe 69,70 were erroneously designated permit no. BC-00-5896.	Fe 69
Patuxent	125.00	09-22 1950	U	-	410	24	31	13.2	09-22 1950	D	Fe 70
Patuxent	24.14	03-31 1982	U,O	-	25	-	-	-	01-25 1946	D	Ff 34
Patapsco	27.59	03-31 1982	C	S	75	10	25	3.0	08-00 1954	D	Ff 54
Patapsco	17.90	03-29 1982	U	-	20	8	22	0.9	08-25 1958	D	Ff 81
Patuxent	31.95	10-14 1981	N	T	128	24	8	16.0	05-16 1969	D,A	Ff 85
Patapsco	7.01	03-29 1982	D	S	25	1	35	0.7	01-23 1978	D	Ff 86
Patapsco	15.77	03-29 1982	D	S	60	2	12	5.0	12-20 1979	D	Ff 87
Patapsco	15.02	03-29 1982	D	S	45	2	10	4.5	08-31 1978	D	Ff 88
Patapsco	18.65	03-30 1982	D	S	5	6	10	0.5	08-27 1976	D	Ff 89
Patuxent	34.00	03-30 1982	I,R	T	400	24	55	7.3	08-09 1970	D,A; G,E,C for test well drilled under permit nos. BA-70-0370, BA-71-0115.	Fg 69
Patapsco	8.78	03-30 1982	D	S	-	-	-	-	-	D	Fg 70
Patapsco	4.01	08-18 1981	D	S	20	1	10	2.0	02-19 1980	D	Fg 71
Patapsco	18.20	08-20 1981	D	S	5	8	6	0.8	07-10 1974	D	Fg 72
Patapsco	13.66	03-29 1982	D	S	10	6	8	1.3	12-28 1973	D	Fg 73

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 U = Unused
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Pump type

 J = Jet
 O = Other
 S = Submersible
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Remarks

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Table 9.—Records of selected wells in the Baltimore area—Continued

USGS Well No.	State Permit No.	Owner	Driller	Completion year	Method of drilling	Altitude of land surface (feet)	Diameter of casing at lsd (inches)	Total depth drilled (feet)	Depth of casing (feet)	Screen intervals (feet below land surface)	Screen diameter (inches)	Finish
Baltimore County (cont.)												
Gc 25	BA-73-8100	Howard Co. Dept. Pub. Works	Branham Contractors Inc.	1981	H	10	4	90	80	80-90	4	G
Gc 26	BA-73-5835	Dancy, James	Frank's Well Drill., Inc.	1978	H	60	4	98	93	93-98	2	G
Gc 27	BA-73-6468	Gray, Aaron	Frank's Well Drill., Inc.	1979	H	75	4	65	58	58-65	3	G
Gf 11	-	Bethlehem Steel Corp. (Sparrows Pt.)	Shannahan Artesian Well Co.	1941	H	10	14	645	423	-	-	-
Gf 78	-	Bethlehem Steel Corp. (Sparrows Pt.)	Shannahan Artesian Well Co.	1937	H	10	12	654	292	292-302 625-633 645-651	8	-
Gf 139	-	Bethlehem Steel Corp. (Sparrows Pt.)	Shannahan Artesian Well Co.	1938	H	10	12	615	520	520-530 555-575 585-615	8	-
Gf 168	-	Bethlehem Steel Corp. (Sparrows Pt.)	Shannahan Artesian Well Co.	1919	H	10	10	308	283	283-304	-	-
Gf 169	-	Bethlehem Steel Corp. (Sparrows Pt.)	Shannahan Artesian Well Co.	1919	H	10	10	224	202	202-222	-	-
Gf 207	BA-01-2428	Bethlehem Steel Corp (Sparrows Pt.)	Shannahan Artesian Well Co.	1954	H	10	18	199	-	-	-	-
Gf 210	BA-02-3182	Bethlehem Steel Corp. (Sparrows Pt.)	Shannahan Artesian Well Co.	1957	H	10	12	692	546	546-553 570-584 654-659 667-674	-	-
Gf 211	BA-02-3183	Bethlehem Steel Corp. (Sparrows Pt.)	Shannahan Artesian Well Co.	1957	H	10	12	694	586	586-594 647-661 668-694	-	-
Gf 212	BA-03-4726	Bethlehem Steel Corp. (Sparrows Pt.)	Shannahan Artesian Well Co.	1960	H	10	12	685	500	500-510 545-557 569-573 658-685	-	-
Gf 220	BA-69-0276	Bethlehem Steel Corp. (Sparrows Pt.)	Shannahan Artesian Well Co.	1969	H	10	12	742	691	691-732	7	S
Gg 13	BA-81-1300	Maryland Port Auth. (Hart-Miller Island)	A.C. Schultes & Sons, Inc.	1983	H	17	6	682	626	626-646	-	G
Gg 14	BA-73-5374	Rocky Pt. County Pk.	Frank's Well Drill., Inc.	1978	H	20	6	64	59	59-64	4	G

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Principal aquifer	Static water level (feet below land surface)	Date	Use	Pump	Yield (gal/min)	Duration of test (hours)	Draw-down (feet)	Specific capacity	Date	Remarks	USGS Well No.
Baltimore County (cont.)											
Patuxent	0	06-11 1981	U,O	-	80	4	90	0.9	06-11 1981	D,G	Gc 25
Patuxent	51.90	04-01 1982	D	S	15	2	10	1.5	09-13 1978	D	Gc 26
Patuxent	37.80	04-01 1982	D	S	10	2	10	1.0	03-12 1979	D	Gc 27
Patuxent	54.80	03-29 1982	O	-	690	-	65	10.6	01-00 1943	G; Wire Mill 12A.	Gf 11
Patapsco Patuxent	50.05	03-29 1982	U,O	T	-	-	-	-	-	D; Rail Mill 25.	Gf 78
Patuxent	112.00	00-00 1939	-	T	550	-	57	9.7	00-00 1939	Coke Oven 31.	Gf 139
Patapsco	10.25	03-29 1982	U,O	-	103	-	-	-	00-00 1942	Town Water 3; USGS observation well.	Gf 168
Patapsco	10.37	03-29 1982	U,O	-	92	-	-	-	01-00 1943	Town Water 4; USGS observation well.	Gf 169
Patapsco	15.78	03-29 1982	U,O	-	600	9	40	15.0	02-26 1954	Coke Oven 40.	Gf 207
Patuxent	52.62	03-29 1982	N,O	T	650	24	89	7.4	11-29 1957	A; Hot Strip 10.	Gf 210
Patuxent	50.87	03-29 1982	U,O	T	650	24	26	25.0	12-12 1957	Blast Furnace 2T.	Gf 211
Patuxent	-	-	N,O	T	695	24	28	24.8	05-09 1960	Blast Furnace 3T.	Gf 212
Patuxent	94.00	12-14 1969	N,O	T	500	24	192	2.6	12-15 1969	D,G,A; Town Water Deep Well 4.	Gf 220
Patuxent	16.33	04-18 1983	D	T	104	8	-	0.8	04-15 1983	D,E,G,A; specific capacity reported by driller.	Gg 13
Patapsco	24.82	03-30 1982	R	S	30	6	16	1.9	03-31 1978	D	Gg 14

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Pump type

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Remarks

 A = Chemical analysis
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Table 10.—Large appropriators and public water supplies utilizing the ground water of the Baltimore area

(Appropriations for less than an average of 10,000 gallons per day (gal/d) are not included)

Quad-range	Name of appropriator or public supply	Appropriation		Well number	Aquifer utilized	Pumpage reported WRA ³	
		GAP ¹ Number	Quantity (gal/d) Average(A) Maximum(M)			12-Month average (gal/d)	Year reported 1980
Anne Arundel County							
Ad	Anne Arundel County Dept. of Public Works Glen Burnie System	AA-69-GAP-019	7,500,000(A) 15,000,000(M)			² 11,797,320	
	Sawmill Creek well field			Ad 23 Ad 40 Ad 41 Ad 67 Ad 68	Patapsco Patapsco Patapsco Patapsco Patapsco	(1,845,000)	
	Dorsey Road well field (non-iron group)			Ad 74 Bd 55 Bd 56 Bd 64 Bd 92 Bd 95	Patapsco Patapsco Patapsco Patapsco Patapsco Patapsco	(2,603,000)	
	Dorsey Road well field (iron group)			Ad 76 Bd 57 Bd 66 Bd 97 Bd 98	Patuxent Patuxent Patuxent Patuxent Patuxent	(877,000)	
	Meade Village wells			Bc 175 Bc 176 Bc 194	Patapsco Patapsco Patapsco	(112,000)	
	Harundale well field			Bd 36 Bd 37 Bd 61 Bd 63	Patapsco Patapsco Patapsco Patapsco	(1,786,000)	
	Phillips Drive well			Bd 101	Patapsco	(656,000)	
	Glendale well			Bd 103	Patapsco	(462,000)	
	Crain Highway wells			Bd 104 Bd 105	Patapsco Patapsco	(487,000)	
	Elvation Road wells Thelma Avenue well			Bd 106 Bd 108	Patapsco Patapsco	(760,000) (208,000)	
	Quarterfield Road well			Bd 109	Patapsco	(733,000)	
Ae	Chemicals Division (or Diamond-Shanrock)	AA-62-GAP-030	910,000(A) 1,300,000(M)	Ae 36	Patuxent	776,925	
Bb	Anne Arundel Co. Dept. of Public Works Maryland City Ft. George G. Meade wells	AA-65-GAP-033	800,000(A) 1,400,000(M)	Bb 64 Bb 65 Bb 66 Bb 69	Patuxent Patuxent Patuxent Patuxent	563,321	
Bb	Colony 7 Motor Inn	AA-60-GAP-024	30,000(A) 40,000(M)	Bb 50 Bb 54 Bb 70	Patuxent Patuxent Patuxent	28,433	
Bb	Holiday Inn-Laurel	AA-69-GAP-009	28,800(A) 100,000(M)	Bb 72 Bb 73	Patuxent Patuxent	269	

¹ GAP = Ground-water Appropriation Permit.
² Subtotals of reported pumpage in parentheses.
³ WRA = Water Resources Administration.

Table 10.—Large appropriators and public water supplies utilizing the ground water of the Baltimore area—Continued

Quad-range	Name of appropriator or public supply	Appropriation			Pumpage reported	
		GAP Number	Quantity (gal/d) Average(A) Maximum(M)	Well number	Aquifer utilized	12-Month average (gal/d)
Anne Arundel County (cont.)						
Bb	Laurel Race Course, Inc.	AA-47- GAP-003	75,000(A) 165,000(M)	Bb 22 Bb 48 Bb 49	Patuxent Patuxent Patuxent	70,638
Bb	Parkway Manor- Econo-Lodge	AA-54- GAP-019	25,000(A) 30,000(M)	Bb 38 Bb 71	Patuxent Patuxent	10,272
Bb	U.S. Army Ft. George G. Meade	AA-69- GAP-021	2,000,000(A) 6,000,000(M)	Bb 68 Bb 71 Bc 164	Patuxent Patuxent Patuxent	348,896
Bc	Anne Arundel County Dept. of Public Works Glen Burnie System	(See entry above in Ad quad)				
Bc	Chesapeake Mobile Homes	AA-57- GAP-007	38,000(A) 46,000(M)	Bc 72 Bc 155	Patapsco Patapsco	35,998
Bc	Nevamar Corp. (formerly Exxon)	AA-70- GAP-012	3,300,000(A) 3,500,000(M)	Bc 1 Bc 20 Bc 40 Bc 47 Bc 157 Bc 165 Bc 171 Bc 173	Patapsco Patapsco Patapsco Patapsco Patapsco Patapsco Patapsco Patuxent	2,319,996 44,079
Bc	Free State Management Co.	AA-73- GAP-025	308,000(A) 540,000(M)	Bc 181	Patuxent	139,227
Bc	Holiday Mobile Estates, Inc.	AA-63- GAP-008	48,000(A) 50,000(M)	Bc 177 Bc 178	Patuxent Patuxent	45,890
Bc	MacMillan Bloedel Pkg. Ltd.	AA-62- GAP-003	65,000(A) 75,000(M)	Bc 182	Patapsco	11,382
Bc	Severn Water Co. (formerly Pioneer City Water Co.)	AA-69- GAP-016	7,500,000(A) 15,000,000(M)	Bc 169 Bc 195	Patapsco Patapsco	405,605
Bc	Province Water Co.	AA-70- GAP-046	350,000(A) 450,000(M)	Bc 193	Patuxent	286,068
Bc	Robinhood Dell Trailer Park (Ridgewood Mobile Home Park)	AA-69- GAP-006	20,000(A) 30,000(M)	Bc 199 Bc 200	Patuxent Patuxent	22,320
Bc	U.S. Army Ft. George G. Meade	(See entry above in Bb quad)				
Bd	Anne Arundel Co. Dept. of Public Works	(See entry above in Ad quad)				
	Rol-Par Village (Pardoe, Roland)	AA-58- GAP-005	26,000(A) 40,000(M)	Bd 69	Patapsco	16,757
Bf	Anne Arundel Co. Board of Educ. (Bodkin Elem Sch.)	AA-70- GAP-013	80,300(A) 87,400(M)	Bf 51	Patapsco	12,329

**Table 10.—Large appropriators and public water supplies utilizing the ground water of the Baltimore area—
Continued**

Quad-range	Name of appropriation or public supply	Appropriation		Well number	Aquifer utilized	Pumpage reported	
		GAP Number	Quantity (gal/d) Average(A) Maximum(M)			12-Month average (gal/d)	Year reported 1980
Baltimore County							
Fe	Eastern Stainless Steel Corp.	BA-56-GAP-006	1,200,000(A) 2,100,000(M)	Fe 59 Fe 64 Fe 66	Patuxent Patuxent Patuxent	964,448	
Fe	Jos. S. Merritt, Inc.	BA-59-GAP-009	20,000(A) 50,000(M)	Fe 68	Patapsco	16,808	
Fe	Jos. E. Seagram & Sons Distillery (formerly Calvert Distillery)	BA-78-GAP-017	633,000(A)	Fe 69	Patuxent	376,548	
Gf	Bethlehem Steel Corp. (Sparrows Point)	BA-46-GAP-003	5,500,000(A) 6,000,000(M)	Gf 210 Gf 211 Gf 212	Patuxent Patuxent Patuxent	3,528,022	
Baltimore City							
1N3E	Hood Vinegar Company	BC-56-GAP-001	86,000(A) 1,200,000(M)	1N3E- 9 1N3E-11	Patuxent Patuxent	79,417	
1S3E	Esskay Quality Meats Co. (or Schludeberg-Kurdle Co.)	BC-58-GAP-001	300,000(A) 350,000(M)	1S3E-45 1S3E-46 1S3E-47	Patuxent Patuxent Patuxent	154,494	
3S5E	Universal Foods Corp. (or Federal Yeast Corporation)	BC-60-GAP-001	3,000,000(A) 3,500,000(M)	3S5E-39 3S5E-40 3S5E-41 3S5E-42 3S5E-43	Patuxent Patuxent Patuxent Patuxent Patuxent	2,585,100	
5S2E	F.M.C. Corporation	BC-60-GAP-001	3,000,000(A) 4,000,000(M)	5S2E-20	Patuxent	417,724	

Table 11.—Selected logs of wells in the Baltimore area—Continued

Anne Arundel County	Thickness (feet)	Depth (feet)	Log type D	Anne Arundel County (cont.)	Thickness (feet)	Depth (feet)	Log type D
Well AA Ad 98 (Altitude: 92 feet)				Well AA Ad 98 (cont.)			
Sand	12	12		Sand, mixed; clay, white	12	285	
Clay, red, white	6	18		Sand, brown, white, fine- medium	9	294	
Clay, red, brown	6	24		Sand; clay, white	1	295	
Clay, brown, sand	4	28		Sand, brown, white, coarse- very coarse	15	310	
Clay, gray	13	41					
Clay, red	6	47		Well AA Ad 99 (Altitude: 12 feet)			D
Clay, gray	22	69					
Clay, red	2	71		Clay, brown, white	7	7	
Clay, white	2	73		Sand	6	13	
Clay, gray	4	77		Clay, white	1	14	
Clay, brown; sand, brown	6	83		Clay, gray	2	16	
Sand, brown, white, coarse; gravel	13	96		Clay, brown	2	18	
Sand; gravel; clay, white	5	101		Sand	2	20	
Clay, white	10	111		Clay, gray	14	34	
Sand, brown, white, medium- coarse	2	123		Sand	1	35	
Sand; clay, white	4	127		Clay, red	2	37	
Clay, red, white	4	131		Clay, gray, red	4	41	
Sand, brown, white, medium- fine	13	144		Clay, gray	13	54	
Clay, white	7	151		Clay, white	1	55	
Sand, brown, white, coarse; gravel	12	163		Clay, red, white	1	56	
Sand, soft	.5	163.5		Clay, red	4	60	
Sand, brown, white, coarse	4.5	168		Clay, white	1	61	
Clay, white	1	169		Clay, brown	2	63	
Sand, brown, white, coarse	16	185		Clay, white	2	65	
Sand; clay, pink	7	192		Sand, brown, white, coarse	17	82	
Clay, red, white; sand	2	194		Clay, white	.6	82.6	
Clay, white	7	201		Sand, brown, white, coarse	2.4	85	
Clay, white; sand	14	215		Clay, white	2	87	
Clay, white	7	222		Sand, white, medium-coarse	5	92	
Clay, red	3	225		Clay, white	7	99	
Clay, red, white	9	234		Rock	1	100	
Sand	1	235		Sand, white	2	102	
Clay, white	4	239		Clay, white	2	104	
Clay, white; sand	22	261		Sand, white, brown; gravel	14	118	
Sand, brown, white, coarse- very coarse	10	271		Clay, white	1	119	
Clay, white	1.5	272.5		Sand, white, brown, medium	16	135	
Sand	.5	273		Rock	6	141	
				Sand, brown, medium	10	151	
				Clay, white	4	155	
				Sand; gravel	2	157	

Log type: D = Driller's log
G = Geologist's log from sample cuttings

Log type: D = Driller's log
G = Geologist's log from sample cuttings

Table 11.—Selected logs of wells in the Baltimore area—Continued

Anne Arundel County (cont.)	Thickness (feet)	Depth (feet)	Log type	Anne Arundel County (cont.)	Thickness (feet)	Depth (feet)	Log type
Well AA Ad 99 (cont.)			D	Well AA Ae 36 (Altitude: 30 feet)			D
Clay, white	5	162		Clay	39	39	
Sand	3	165		Sand	4	43	
Clay, white, brown; sand	7	172		Clay, sandy	43	86	
Rock	.4	172.4		Sand	15	101	
Clay, red	20.6	193		Clay	16	117	
Clay, white; sand	23	216		Sand	5	122	
Sand, brown, white, medium	9	225		Clay	30	152	
Clay, white	3	228		Sand	12	164	
Sand	2	230		Clay	18	182	
Clay, white	.6	230.6		Sand	14	196	
Sand	1.4	232		Clay, sandy	18	214	
Clay, white	3	235		Clay, red	8	222	
Sand, brown, white, fine	5	240		Sand	13	235	
Sand, brown, white, medium-coarse; clay streaks, white	19	259		Clay, red	91	326	
Clay, white	1	260		Sand, white	96	422	
Sand, brown, white, medium-coarse	5	265		Clay, sandy	13	435	
Clay, white	4	269		Sand	71	506	
Clay, white; sand	5	274		Clay	10	516	
Sand	3	277		Sand	8	524	
Clay; red, white	4	281		Clay	4	528	
Rock, soft	.4	281.4		Sand; gravel	29.5	557.5	
Clay, white; sand	10.6	292		Clay; sand; mica	9.5	567	
Sand	5	297					
Sand; clay, white	31	328		Well AA Bd 97 (Altitude: 75 feet)			D
Clay, white	8	336		Top soil	3	3	
Sand	2	338		Sand, brown streaks; sandrock; clay, yellow, white	13	16	
Clay, white	2	340		Clay, white; sandrock	5	21	
Sand	4	344		Clay, white with streaks	2	23	
Clay, white	.6	344.6		Clay, white; streaks of sand, white, fine	10	33	
Sand	1.4	346		Clay, white; streaks of sand, white, fine	9	42	
Clay, white	1	347		Sand, white, fine	13	55	
Sand	8	355		Clay, white; streaks of sand, white, fine	4	59	
Clay, red, white	.6	355.6		Sand, brown, medium	2	61	
Sand	.4	356		Clay, white	1	62	
Clay, red, white	1	357		Sand, brown, coarse; gravel	34	96	
Sand	3.2	360.2		Clay, white; streaks of rock	4	100	
Clay, white	1.8	362		Clay, hard, red	28	128	
Sand, water bearing	9	371		Clay, brown, white, hard	10	138	
				Clay, brown, gray, hard	9	147	
				Clay, gray streaks; sand	6	153	

Log type: D = Driller's log
G = Geologist's log from sample cuttings

Log type: D = Driller's log
G = Geologist's log from sample cuttings

Table 17.—Selected logs of wells in the Baltimore area—Continued

Anne Arundel County (cont.)	Thickness (feet)	Depth (feet)	Log type D	Baltimore City	Thickness (feet)	Depth (feet)	Log type D
Well AA Bd 97 (cont.)				Well IN3E-9 (Altitude: 110 feet)			
Clay, yellow, red, white streaks; sand	4	157		Clay, red	10	10	
Sand, white, coarse	9	166		Clay, white	10	20	
Clay, red, white streaks; sand	9	175		Sand, coarse	10	30	
Rocks, hard	2	177		Clay, white	10	40	
Clay, white, yellow, red clay, hard	6	183		Gravel; sand	5	45	
Clay, brown, yellow, hard	9	192		Clay, red	15	60	
Clay, gray	11	203		Clay, red	8	68	
Clay, gray; rock, 2"-6" thick	19	222		Clay, red	12	80	
Clay, gray, sandy, hard	8	230		Clay, white	2	82	
Clay, gray, hard, streaks of rock	19	249		Sand	10	92	
Sand, fine; wood	6	255		Clay, white	6	98	
Clay, hard, gray	12	267		Gravel, sand	11	109	
Sand, medium; wood	13	280		Clay, white	2	111	
Clay, brown, white, hard	10	290		Sand	4	115	
Clay, white, gray, soft; sand streaks	52	342		Clay, white	5	120	
Clay, brown, red, yellow hard	11	353		Shale	6	126	
Clay, brown with streaks, hard	9	362		Clay, white	4	130	
Clay, white, brown, streaks, sand	8	370		Rock, soft	10	140	
Rock, red	.5	370.5		Rock, soft	15	155	
Clay, white streaks, sand	12.5	383		Well IN5E-4 (Altitude: 20 feet)			D
Sand, white, medium	48	431		Sand; gravel	10	10	
Clay, red, hard	13	444		Clay, gray	4	14	
Clay, mixed, hard	5	449		Sand	33	47	
Clay, gray; sand, wood streaks	12	461		Stone; clay, red	7	54	
Clay, gray, white	7	468		Clay, red, white	44	98	
Sand, white, medium; wood with streaks of clay, white	8	476		Sand, water bearing	17	115	
Clay, gray, soft, sand, wood streaks	16	492					
Sand, gray; wood; (w.b.)	32	524					
Clay, gray	2	526					
Sand, gray, coarse, (w.b.)	10	536					
Clay, white	3	539					
Clay, green, sandy	6	545					
Rock, green, white	3	548					

Log type: D = Driller's log
G = Geologist's log from sample cuttings

Log type: D = Driller's log
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Table 11.—Selected logs of wells in the Baltimore area—Continued

Baltimore City (cont.)				Baltimore City (cont.)			
	Thickness (feet)	Depth (feet)	Log type		Thickness (feet)	Depth (feet)	Log type
Well 1S3E-47 (Altitude: 55 feet)				Well 3S4E-15 (Altitude: 20 feet)			
Fill	4	4	D	Clay, brown	15	15	D
Clay, red, hard	19.5	23.5		Sand	2	17	
Sand, fine, brown	20.5	44		Clay, gray	4	21	
Clay, red, white, hard	23	67		Sand; gravel	1	22	
Rock	1	68		Clay, gray	8	30	
Clay, red, very hard	56	124		Sand; gravel	10	40	
Rock, hard	1	125		Clay, white	1	41	
Sand, white, hard-packed	13	138		Sand	5	46	
Sand, white, very coarse	22	160		Clay, red, white	8	54	
Clay, red, white, sandy	8	168		Clay, white	14	68	
Rock	5	173		Sand	6	74	
Well 3S2E-5 (Altitude: 15 feet)				Well 3S4E-15 (Altitude: 20 feet)			
			G	Clay, white; sand	12	86	
Fill; cinders, bricks, soil	10	10		Sand	19	105	
Clay; silt; red-gray; slightly sandy slow drilling	20	30		Clay, white	3	108	
Clay, red, gray, white, yellow; silt	10	40		Sand	6	114	
Clay; red, streaks of white, yellow, stiff	20	60		Clay, white	1	115	
Clay; red, yellow, white; silt, tough drilling	18	78		Sand	13	128	
Sand; easier drilling	10	90		Clay, red	26	154	
Clay, white; silt	4	94		Sand, brown	9	163	
Sand; silt	26	120		Clay, red, white	25	188	
Sand, coarse, layers of white silt, clay	26	146		Clay, white	14	202	
Sand, coarse, layers of silt, clay, some gravel	20	166		Sand	6	208	
Sand, coarse; gravel	14	180		Clay, white	7	215	
Gravel, very hard drilling	7	187		Sand, brown, white, coarse	15	230	
				Clay, white	9	239	
				Sand, coarse; gravel	21	260	
				Clay, white	4	264	
				Sand; clay, white	2	266	
				Sand; gravel	3	269	
				Clay, white	2	271	
				Sand; gravel	14	285	

Log type: D = Driller's log
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G = Geologist's log from sample cuttings

Table 11.—Selected logs of wells in the Baltimore area—Continued

Baltimore City (cont.)	Thickness (feet)	Depth (feet)	Log type G	Baltimore City (cont.)	Thickness (feet)	Depth (feet)	Log type G
Well 3S5E-46 (Altitude: 10 feet)				Well 3S5E-46 (cont.)			
Fill; soil; bricks; sand; pebbles; silt, white-gray, green, red	10	10		Clay	1	337	
Sand, white, medium-grained	10	20		Sand, few pebbles	23	360	
Sand, white, coarse	10	30		Sand	16	376	
Sand, medium; streaks of clay, white	10	40		Gravel	8	384	
Sand, coarse, white	4	44		Sand, silty	2	386	
Sand, coarse, white	8	52		Iron concretion about 1 ft thick with lignite, gravel	8	394	
Hard layer, tough drilling	6	58		Clay, yellow (saprolite?)	2	396	
Clay, gray, white; sandy	2	60		Clay, white, silty with black fibrous structures	12	408	
Clay, red-brown, white, gray; sandy	5	65					
Clay, red, white, no sand	15	80		Well 5S2E-20 (Altitude: 15 feet)			D
Clay, red, clean	10	90		Mud, gray with wood	52	52	
Clay, red, light brown; silty towards bottom	20	110		Gravel; clay; iron ore streaks	6	58	
Clay, blue-gray; sand streaks about 10 cm. thick	10	120		Clay, white, hard	10	68	
Clay, blue-gray; slightly silty with sand streaks about 10 cm. thick	10	130		Clay, white, pink, sandy	7	75	
Clay, red, white, silty	10	140		Gravel	1	76	
Clay, red, white, gray; silty, sandy	20	160		Sand	13	89	
Clay, mixed; not much sand	4	164		Clay, white and pink	26	115	
Clay, red; no sand, silt	12	176		Sand, white	14	129	
Sandy layer	7	183		Clay, white, sandy	6	135	
Sand	17	200		Clay, white	7	142	
Sand; clay	20	220		Clay, white, sandy	3	145	
Sand, fine-grained with clay, silt	10	230		Sand, white	6	151	
Clay, yellow, silty	6	236		Clay, white	6	157	
Clay, sandy	4	240		Clay, white, sandy	2	159	
Sand, yellow with clay	5	245		Sand	6	165	
Clay, yellow, silty	7	252		Clay, white, sandy	3	168	
Sand	24	276		Clay, white and red	10	178	
Clay	1.5	277.5		Clay, sandy	9	187	
Sand, gravel	16.5	294		Clay, white	8	195	
Clay, white, red, tough	4	298		Clay, white, sandy	8	203	
Sand, clay mixed	2	300		Sand	18	221	
Clay (silt) white; thin layers of sand	8	308		Sand; gravel	13	234	
Sand, fine, well sorted	14	322		Clay; gravel	8	242	
Hard layers, possibly clay	4	326		Sand	4	246	
Sand, clean	10	336		Sand; gravel	18	264	
				Clay	5	269	
				Sand; gravel	8	277	
				Clay; gravel	6	283	
				Clay	2	285	
				Clay, sandy	10	295	
				Clay	5	300	

Log type: D = Driller's log
G = Geologist's log from sample cuttings

Log type: D = Driller's log
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Table 11.—Selected logs of wells in the Baltimore area—Continued

Baltimore City (cont.)			Baltimore County				
	Thickness (feet)	Depth (feet)	Log type		Thickness (feet)	Depth (feet)	Log type
Well 7S4E-1 (Altitude: 40 feet)			D	Well BA Eg 146 (Altitude: 5 feet)			D
Clay, white, brown; sandy	20	20		Clay; brown	3	3	
Clay, gray, red	22	42		Sand	3	6	
Clay, mixed	57	99		Clay, brown	1	7	
Clay, gray	13	112		Sand	21	28	
Clay, red, white	57	169		Clay, white, brown	2	30	
Sand, white, coarse	12	181		Sand, brown	12	42	
Clay, white	17	198		Clay, white, red	4	46	
Sand, white	24	222		Sand	2	48	
Clay, white	3	225		Clay, white, red	7	55	
Sand, white, medium	15	240		Clay, white, sand	5	60	
Clay, red, white, hard	40	280		Sand, brown, white, coarse	7	67	
Clay, red, hard, tough	172	452		Clay, red, white	4	71	
Clay, mixed, not as tough	38	490		Clay, brown	3	74	
Rock	1	491		Clay, white, red	7	81	
Clay, mixed; wood	20	511		Clay, red, white	9	90	
Sand, fine	2	513		Clay, white	4	94	
Clay streaks, sandy	40	553		Sand, fine	7	101	
Sand, white, medium	55	608		Clay, white	2	103	
Sand, coarse	14	622		Sand	1	104	
Clays, mixed; mica	16	638		Clay, gray	4	108	
				Clay, red	3	111	
				Clay, gray	8	119	
				Sand, brown, white	6	125	
				Clay, white	.5	125.5	
				Sand, clay	4.5	130	
				Rock	.5	130.5	
				Clay, white	5.5	136	
				Clay, red	5	141	
				Clay, red, white	14	155	
				Clay, red	26	181	
				Clay, gray	15	196	
				Sand, white, blue, coarse	5	201	
				Sand; gravel	9	210	
				Clay, white	8	218	
				Clay, white	13	231	
				Sand; clay, white	11	242	
				Sand	2	244	
				Clay, gray	18	262	
				Sand	6	268	
				Clay, white	8	276	
				Clay, red	9	285	
				Rock			

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 G = Geologist's log from sample cuttings

Log type: D = Driller's log
 G = Geologist's log from sample cuttings

Table 11.—Selected logs of wells in the Baltimore area—Continued

Baltimore County (cont.)				Baltimore County (cont.)			
	Thickness (feet)	Depth (feet)	Log type		Thickness (feet)	Depth (feet)	Log type
Well BA Fe 52 (Altitude: 190 feet)				Well BA Fe 70 (cont.)			
			D				D
Clay, red, gray	5	5		Sand, free	17	110	
Clay, gray	20	25		Clay, red	31	141	
Clay, yellow	30	55		Sand, free	5	146	
Sand; clay	5	60		Clay, red, white, pink	4	150	
Clay, yellow	4	64		Clay, white	33	183	
Sand; clay	24	88		Clay, brown, white, sandy	15	198	
Sand; gravel	22	110		Sand, coarse, free	18	216	
Sand, water bearing	15	125		Clay, sandy	24	240	
				Sand, coarse, free	20	260	
Well BA Fe 64 (Altitude: 45 feet)				Well BA Fe 70 (cont.)			
			D	Clay, sandy	25	285	
Clay, yellow, white	8	8		Sand, white, fine; clay	42	327	
Gravel; clay	6	14		Sand, brown, white, free	19	346	
Clay, red, white	6	20		Clay, sandy	11	357	
Iron ore	.5	20.5		Sand, free	15	372	
Clay, mixed	18.5	39		Clay, white, pink and gray	17	409	
Sand, clay	13	52		Sand, coarse, free	7	416	
Rock, hard	.5	52.5		Sand, white, coarse, free	24	440	
Clay, mixed	120.5	173		Sand, brown, coarse, free	21	461	
Crusty	.2	173.2		Sand, white, coarse, free	7	468	
Sand, mixed; clay	19.8	193		Clay, gray with wood	4	472	
Rock, hard	.6	193.6		Sand, free; gravel	23	495	
Sand, yellow, red	17.4	211		Gravel; clay with mica	18	513	
Clay; sand	24	235					
Sand, white	11	246		Well BA Ff 85 (Altitude: 22 feet)			
Clay, mixed	21	267					D
Sand, white	44	311		Clay, brown	24	24	
Rock, crusty	.5	311.5		Clay, green	63	87	
Clay, crusty and greenish	13.3	324.8		Sand, white	14	101	
				Clay, mixed	94	195	
Well BA Fe 70 (Altitude: 55 feet)				Well BA Ff 85 (Altitude: 22 feet)			
			D	Clay, sand	49	244	
Sand	10	10		Clay, mixed	74	318	
Clay, white with crusts of iron ore	14	24		Clay, sand	35	353	
Clay, white with crusts of iron ore	8	32		Rock	1	354	
Clay, white, brown	8	40		Clay, mixed	83	437	
Clay, red and white	11	51		Sand; clay, streaks	40	477	
Sand, white, coarse	7	58		Clay, mixed	81	558	
Clay	3	61		Sand, white	27	585	
Gravel, fine, free	3	64		Clay, mixed to rock	30	615	
Clay, white, yellow, brown	6	70					
Clay, white, sandy	23	93					
Log type: D = Driller's log				Log type: D = Driller's log			
G = Geologist's log from sample cuttings				G = Geologist's log from sample cuttings			

Table 11.—Selected logs of wells in the Baltimore area—Continued

Baltimore County (cont.)	Thickness (feet)	Depth (feet)	Log type	Baltimore County (cont.)	Thickness (feet)	Depth (feet)	Log type
Well BA Fg 69 (Altitude: 15 feet)			D	Well BA Gf 78 (cont.)			D
Clay, mixed	734	734		Clay	1	464	
Sand	5	739		Free	2	465	
Clay	2	741		Clay	10	475	
Sand, white, medium	30	771		Clay, sandy	6	482	
Clay	4	775		Sand; some wood; some gravel	5	487	
Sand	20	795		Clay	.5	487.5	
Rock	-	795		Sand, free	.5	488	
				Clay, hard	1	489	
Well BA Gf 78 (Altitude: 10 feet)			D <u>1</u> /	Sand, free	1	490	
Fill	10	10		Clay	7	497	
Clay, lead-colored	20	30		Sand; some gravel	2	499	
Sandy	30	60		Clay	2	501	
Clay	65	125		Clay, hard	1.5	502.5	
Gravel	15	140		Sand, free	.5	503	
Sandy	45	185		Clay, hard	13.5	516.5	
Clay	20	205		Rock	.5	517	
Sandy	20	225		Sandy	3.5	526.5	
Clay, hard	25	250		Rock	.3	526.8	
Rock	1	251		(Not reported)	.7	527.5	
Clay, hard	29	280		Rock	4	531.5	
Clay, white, tough	5.5	285.5		Sandy, with hard places	6.5	538	
Sand, free	7.5	293		Clay, tough	2	540	
Gravel, free; clay in streaks	8	301		Hard places	8	548	
Clay, red, hard	.5	301.5		Clay	2.5	550.5	
Clay, blue, tough	63.5	365		Rock	.3	550.8	
Rock	.3	365.3		Clay, hard	10.2	561	
Clay	15.2	380.5		Sand, hard	1	562	
Rock	.5	381		Clay	2	564	
Clay, softer	17	398		Sand	3	567	
Very sandy	17	415		Rock	1.7	568.7	
Clay	2	417		Clay, hard	9.8	578.5	
Sand	2	419		Sand	1.5	580	
Sand, free	5	424		Clay	9	589	
Clay, tough	.5	424.5		Sandy	1	590	
(Not reported)	4.5	429		Clay, lead-colored	11	601	
Free	6	435		Sand	1	602	
Tough	3.5	438.5		Clay	14.3	616.3	
Sandy	18.5	457		Drifted	2.7	619	
Clay	5	462		Gravel	5	624	
Sand	1	463		Hard	.5	624.5	
				Sand and gravel, free	4.5	629	
				Clay, tough	9.3	638.3	
				Clay	1.2	639.5	
				Hard	.3	639.8	
				Gravel	14.7	654.5	

Log type: D = Driller's log
G = Geologist's log from sample cuttings

1/ Bennett, Robert R., and Meyer, Rex R.; 1952, pp 414-416.

Log type: D = Driller's log
G = Geologist's log from sample cuttings

Table 11.— Selected logs of wells in the Baltimore area—Continued

Baltimore County (cont.)	Thickness (feet)	Depth (feet)	Log type G	Baltimore County (cont.)	Thickness (feet)	Depth (feet)	Log type G
Well BA Gg 13 (Altitude: 17 feet)				Well BA Gg 13 (cont.)			
Fill; sand, fine-coarse	20	20		Sand, white medium grained with clay, silt	17	457	
Sand, fine-medium, some coarse with lignite	20	40		Sand	1	458	
Clay, gray, sandy	10	50		Clay, red, drilling tough	42	500	
Clay, gray, interbedded with sandy clay layers; lignite common in sandy portion; some shell fragments	10	60		Clay, red, dark gray; drilling difficult	24	524	
Clay, gray, slightly silty with maroon streaks; fresh water shell fragments abundant	20	80		Sand	2	526	
Clay, gray, slightly silty; shell fragments abundant; some lignite in cuttings	40	120		Clay red, dark gray; drilling difficult	16	542	
Clay, red with lignite	20	140		Clay, red, dark gray interbedded	64	606	
Clay, red with streaks of clay, gray; silty	10	150		Sand	4	610	
Clay, dark gray, organic-rich with red streaks	24	174		Clay	6	616	
Sand	2	176		Sand	4	620	
Clay, gray, red	4	180		Clay	4	624	
Clay, gray, red, silty with lenses of sandy material	12	192		Sand, fine; silt, yellow, white, red interbedded	36	660	
Sand streaks	8	200		Sand	12	672	
Sand, white, fine; streaks of silt, clay; easy drilling	56	256		Clay, hard	9	681	
Clay; silty	4	260					
Sand, fine-medium; clay, gray; shells	10	270					
Clay, gray, white interbedded with sand, fine-medium	10	280					
Clay, gray, white; sand, very fine - fine, easy drilling	20	300					
Sand, fine-medium	7	307					
Clay, red, white streaks	13	320					
Clay, red, hard	10	330					
Clay, red, white, yellow, silty; sand streaks	34	364					
Sand, white, fine interbedded with clay, silt	16	380					
Clay, red, white with sand and silty clay lenses	14	394					
Clay, hard drilling	26	420					
Sand	2	422					
Clay, red, white, yellow, silty	12	434					
Silt, sandy	6	440					

Log type: D = Driller's log
G = Geologist's log type from sample cuttings

Log type: D = Driller's log
G = Geologist's log type from sample cuttings

Table 12.—Exchangeable cation composition of fine-grained material from the upper part of the Patuxent Formation and Arundel Formation

Sample interval (ft below land surface)	Exchangeable cation composition									
	umols/100 gms					mole fraction (percent)				
	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Total	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Total
Well BA-Gg-13										
¹ 460-480	1.69	0.523	0.082	0.174	2.49	68.5	21.2	3.3	7.0	100.0
¹ 500-520	4.05	1.11	.16	.451	5.77	70.1	19.2	2.7	7.8	99.8
¹ 540-560	3.10	1.31	.099	.47	4.98	62.2	26.3	2.0	9.4	99.9
² 580-600	2.63	1.17	.10	.40	4.30	61.1	27.2	2.3	9.3	99.9
² 620-640	.790	.357	.026	.13	1.30	60.6	27.4	2.0	9.9	99.9
Well 3S5E-46										
¹ 100-120	0.72	0.41	0.021	0.153	1.30	55.2	31.4	1.6	11.7	99.9
¹ 150-160	.95	.463	.015	.20	1.63	58.3	28.4	.9	12.2	99.8
² 180-200	.50	.225	.0065	.07	.80	62.5	28.1	.08	8.7	99.4
² 340-350	.10	.05	.0007	.01	.16	62.2	31.1	.4	6.2	99.9
Well 5S2E-24										
¹ 180-200	0.265	0.127	0.0085	0.09	0.49	54.0	25.9	1.7	18.3	99.9
² 200-220	.225	.105	.0067	.072	.41	54.8	25.6	1.6	17.5	99.5
² 260-280	.187	.078	.0035	.022	.29	64.3	26.9	1.2	7.5	99.9

¹ Sample from Arundel Formation.

² Sample from upper Patuxent Formation.

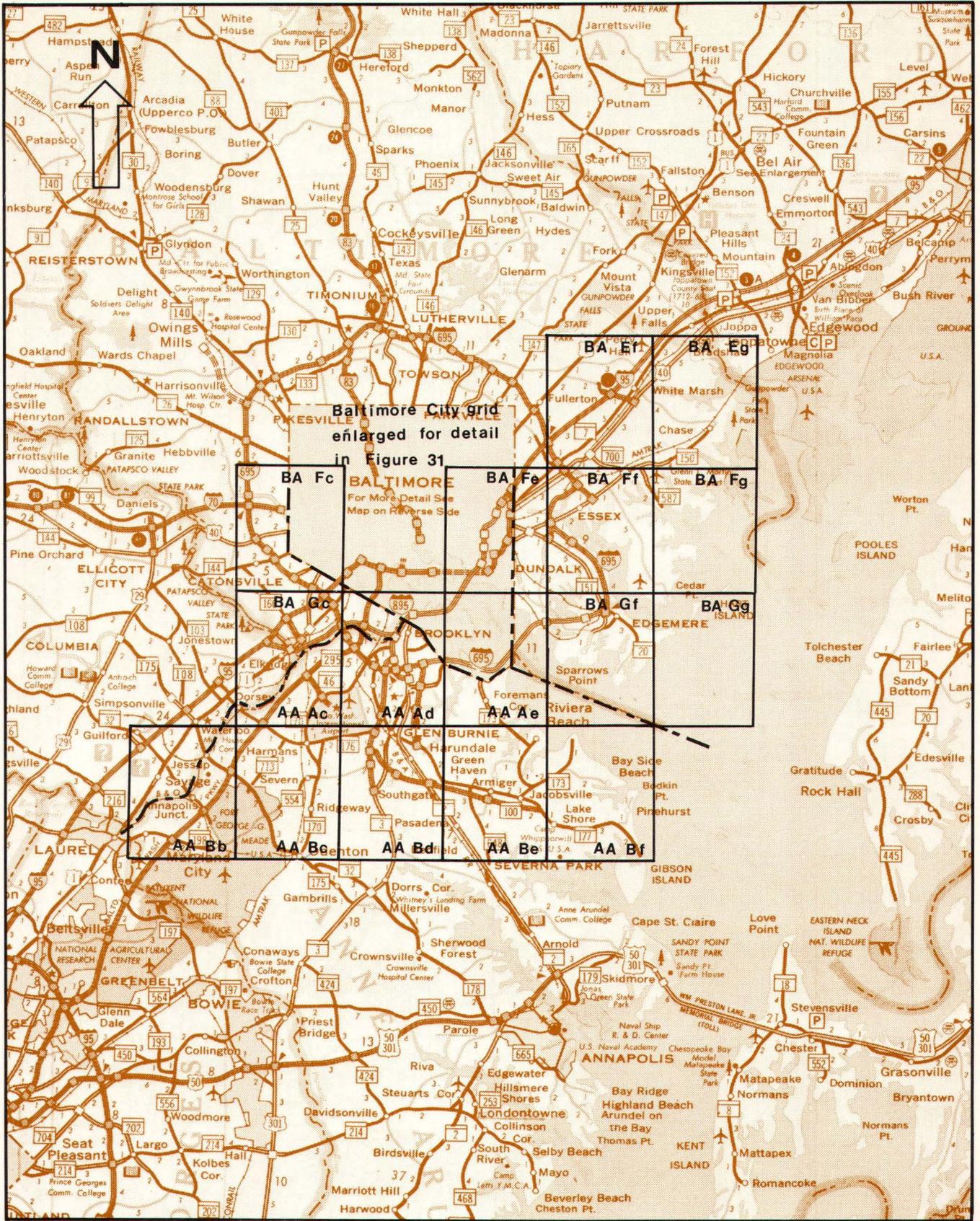


Figure 30.—Locations of 5-minute county quadrangles.



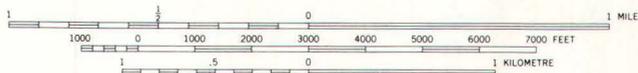
Quadrangle AA Ac, BA Gc



CONTOUR INTERVAL 20 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929



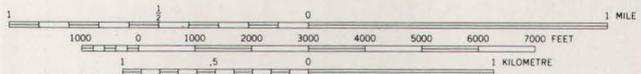
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CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929



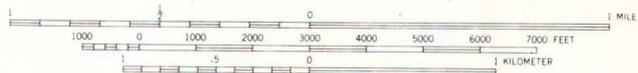
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CONTOUR INTERVAL 10 FEET
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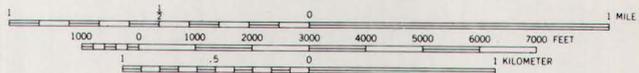
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CONTOUR INTERVAL 20 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929



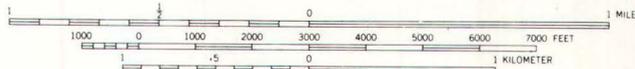
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CONTOUR INTERVAL 20 FEET
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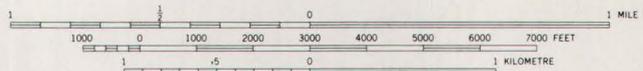
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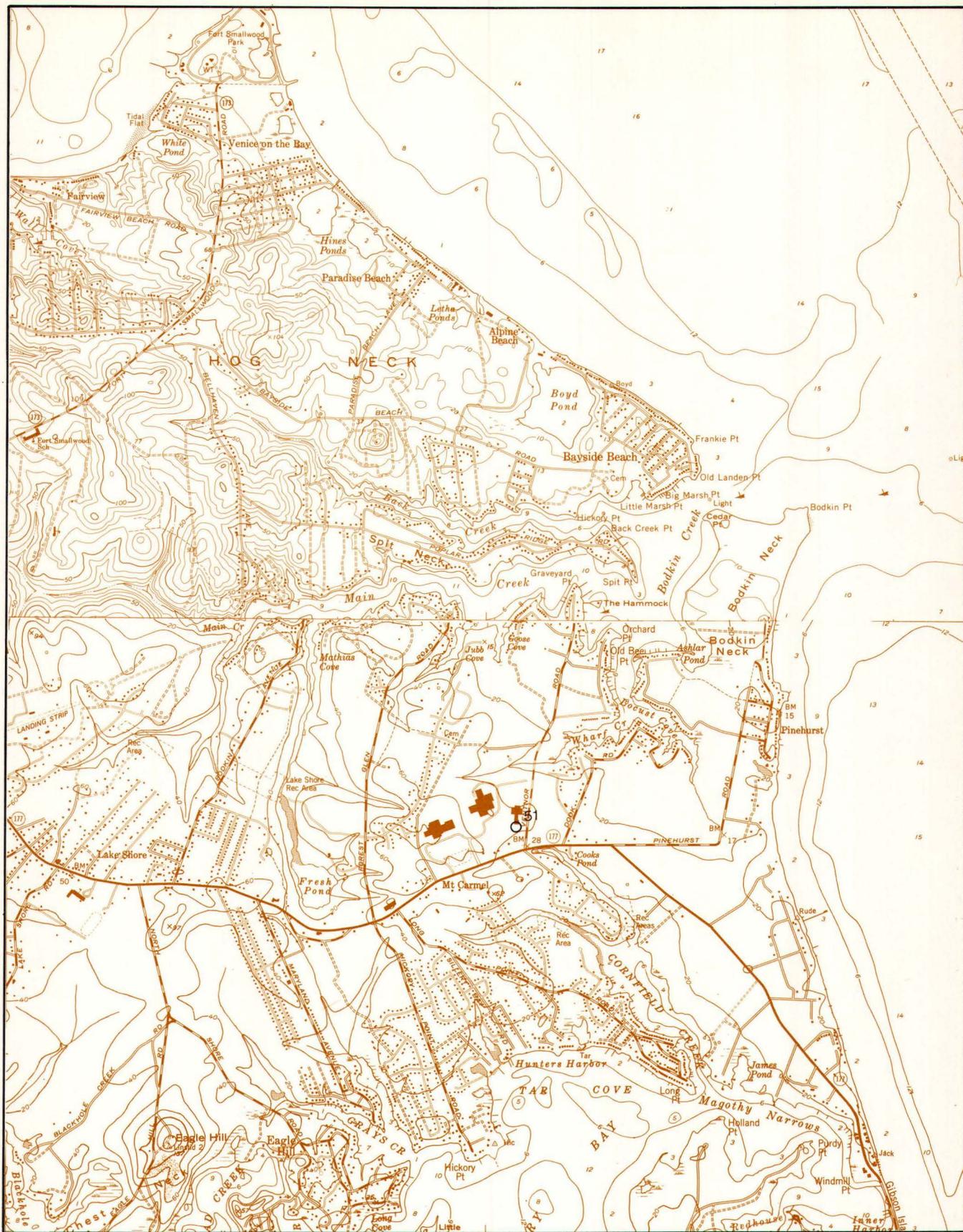
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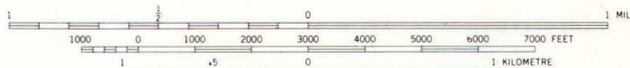
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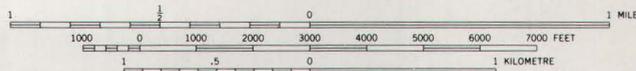
Quadrangle AA Bf



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 NATIONAL GEODETIC VERTICAL DATUM OF 1929



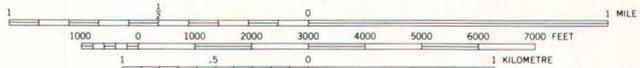
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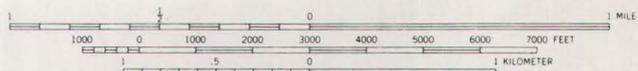
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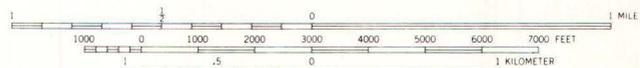
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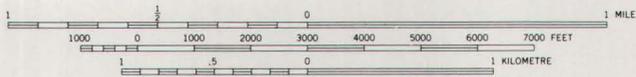
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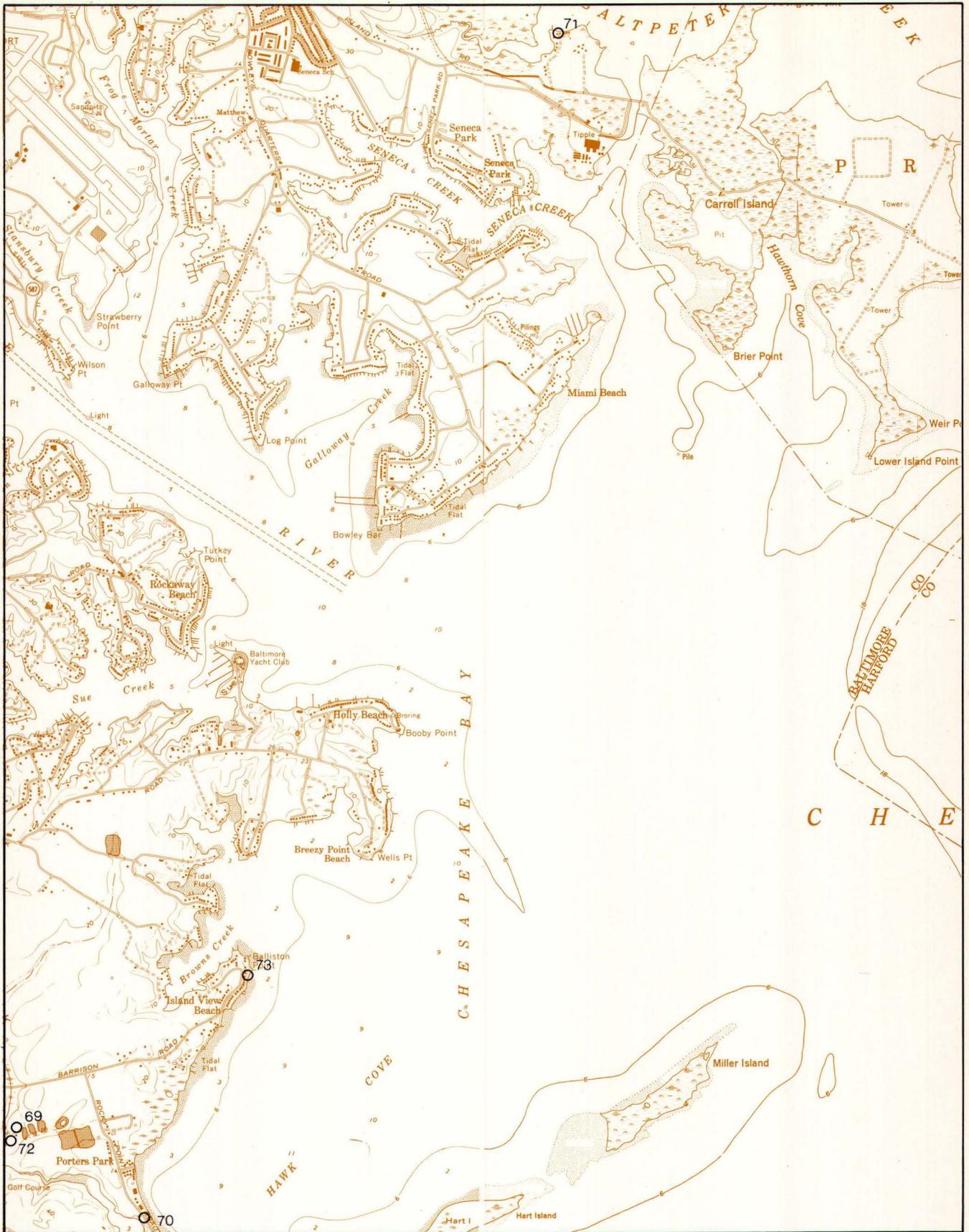
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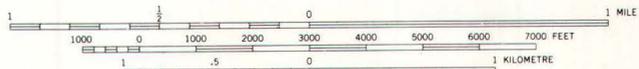
Quadrangle BA Ff



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NATIONAL GEODETIC VERTICAL DATUM OF 1929



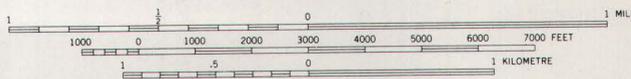
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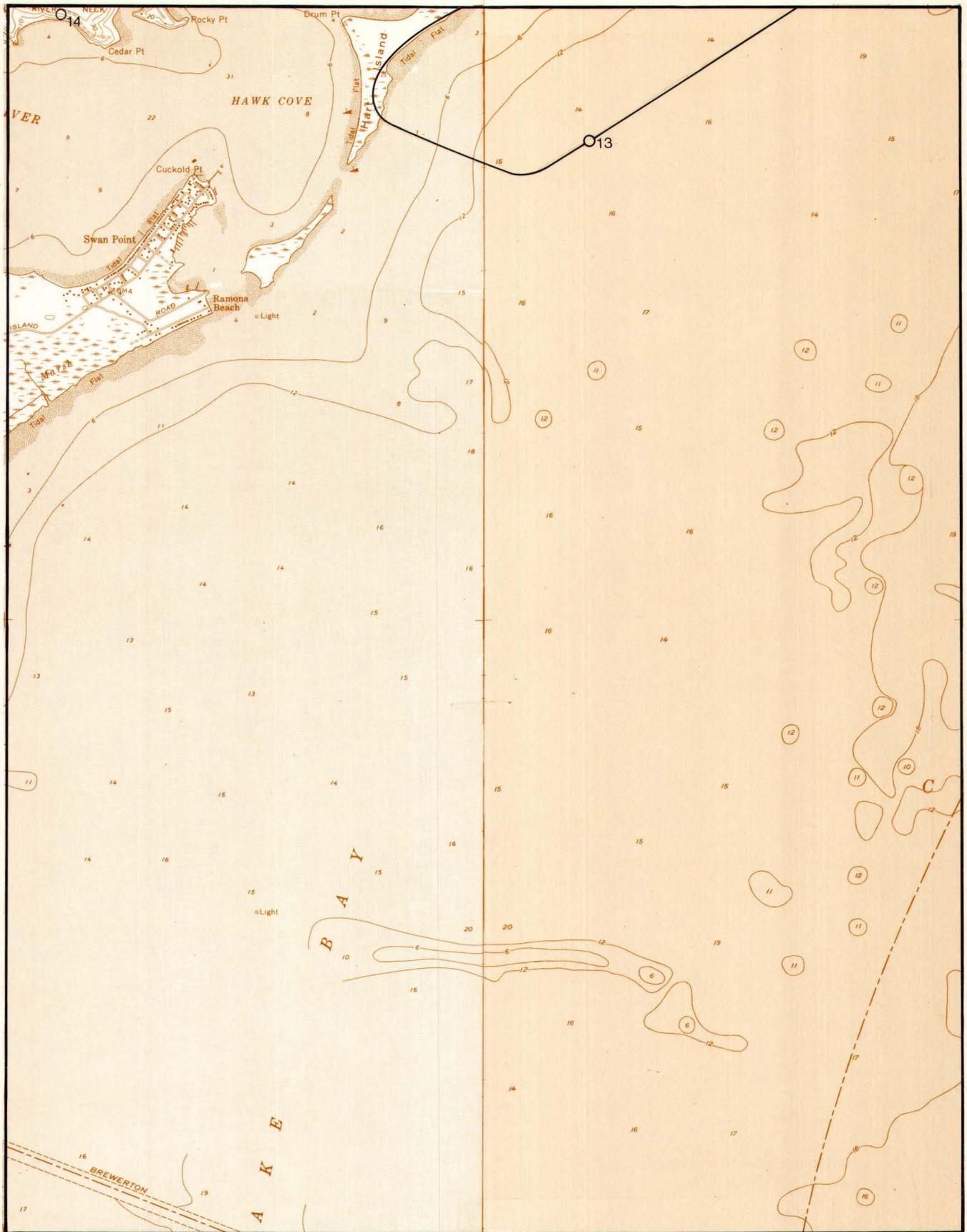
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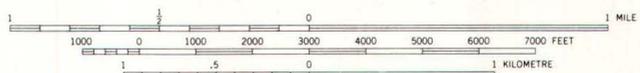
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Quadrangle BA Gg



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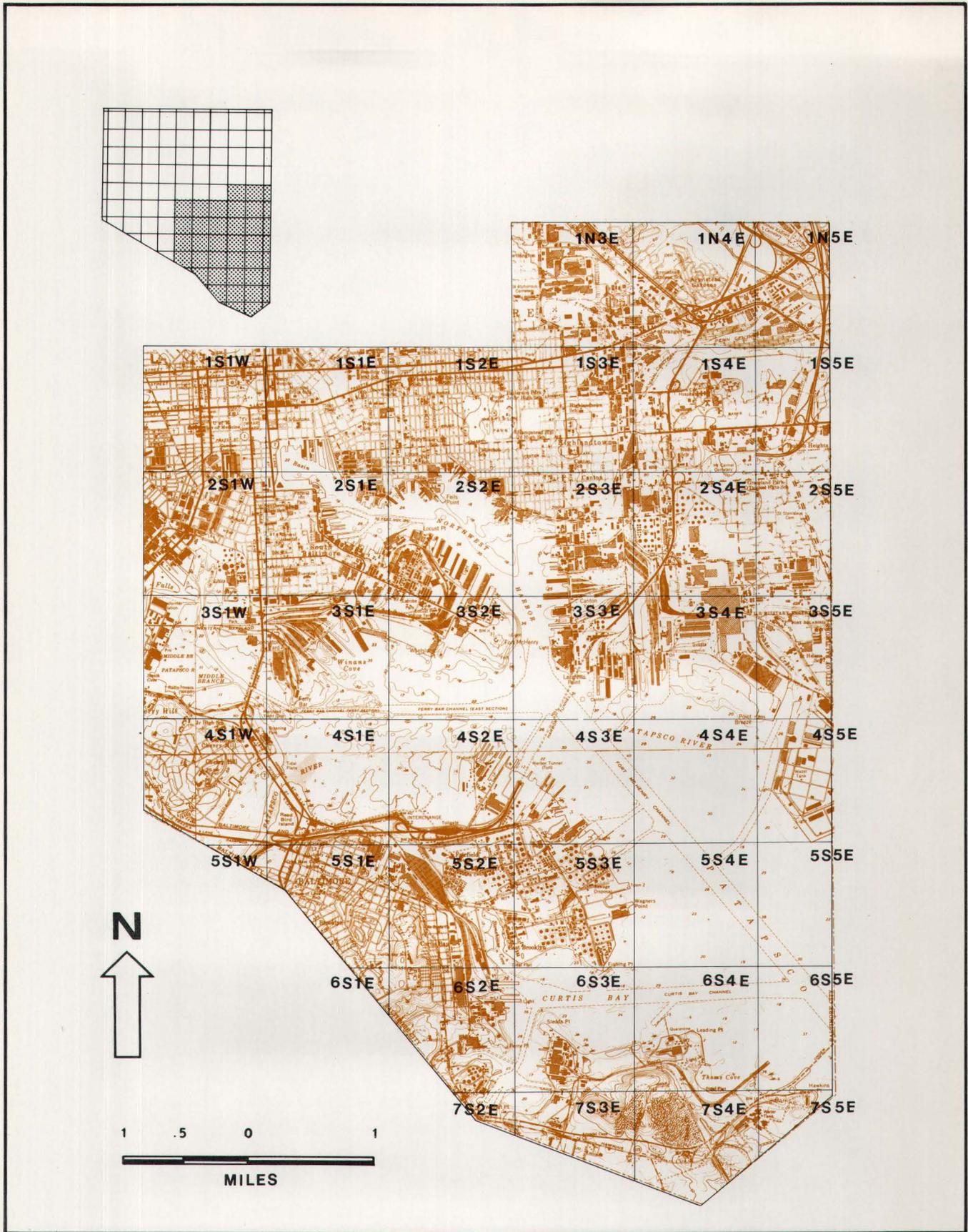
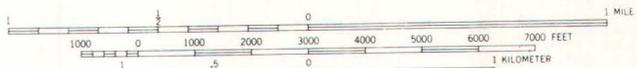
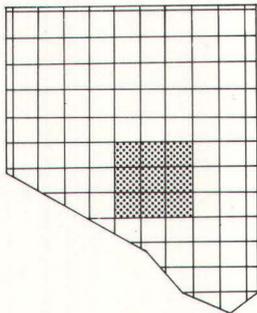
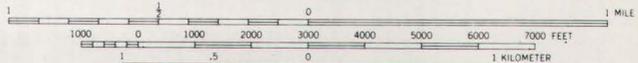
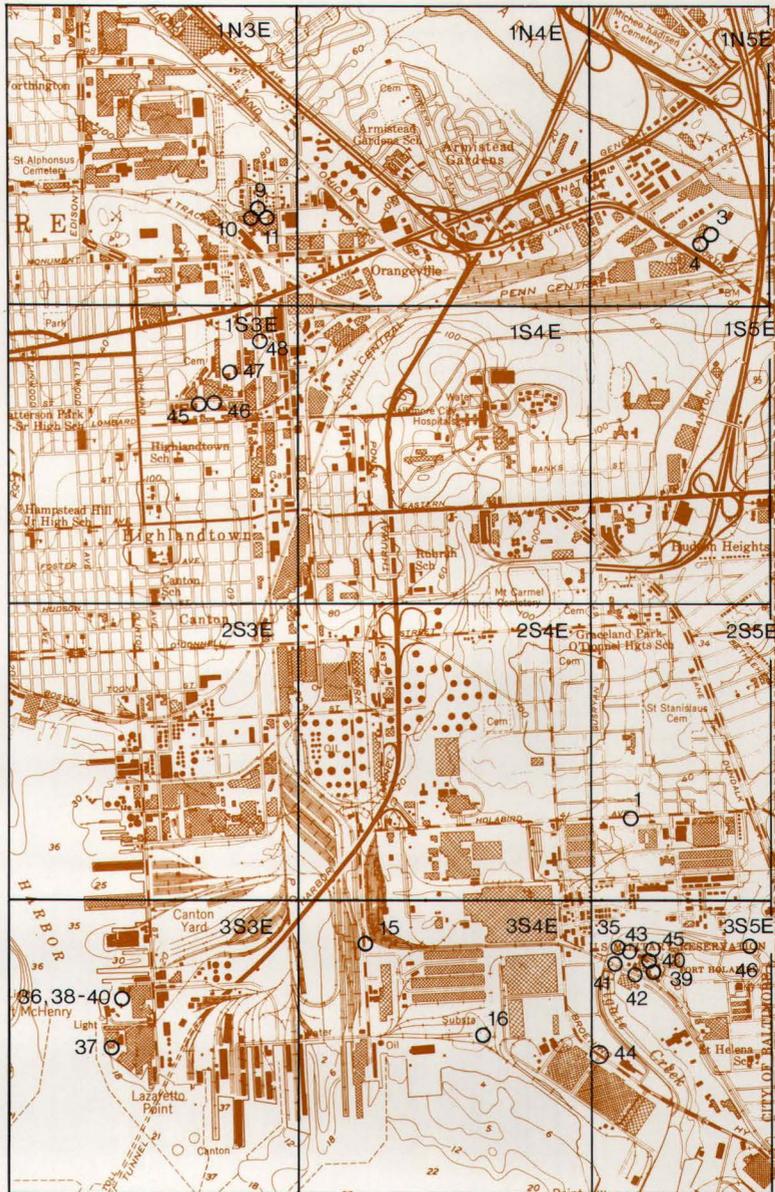
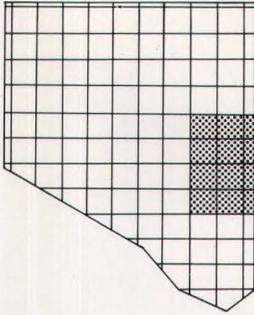


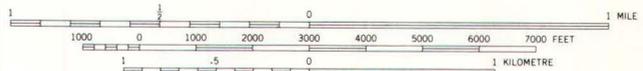
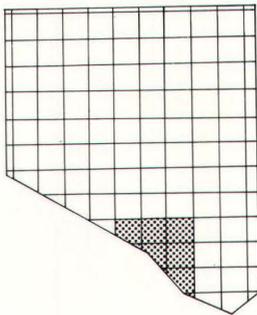
Figure 31.—Locations of Baltimore City 1-mile squares.



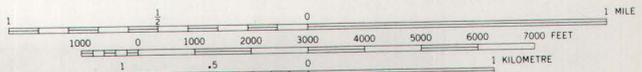
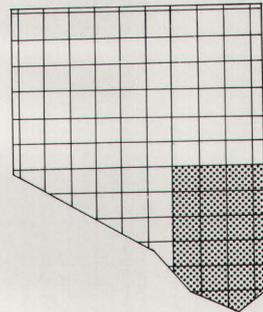
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