NOTES ON THE GEOLOGY AND GROUND-WATER RESOURCES OF THE CAMBRIDGE AREA, MARYLAND

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ABSTRACT

A recent request for a permit from the Maryland Department of Geology, Mines and Water Resources to develop water from the "400-foot" aquifer at Cambridge, Md., resulted in this brief cooperative study of water capabilities there. It is estimated that the "400-foot" aquifer has yielded 21 billion gallons of water at Cambridge since the first well was drilled in 1888. At present it is yielding about 900 million gallons a year. Nonpumping water levels have declined from several feet above sea level to about 82 feet below sea level, and pumping levels are now about 160 feet below sea level.

The only other aquifer now producing at Cambridge is a Cretaceous sand lying at a depth of about 950 feet. It is currently yielding 210 million gallons a year to three wells, the deepest of which - and the deepest drilled so far at Cambridge - is 977 feet deep. A sand lying above the "400-foot" aquifer in a part of the area is capable of yielding some water but is not now tapped by producing wells.

The "400-foot" aquifer is identified as of Jackson age (Eocene). The sand appears to extend at least 25 miles to the southwest, 44 miles to the south, 6 miles to the northwest, and an unknown distance to the east and northeast. It apparently wedges out along a line about 6 miles to the northwest, but water may enter it from the underlying Nanjemoy and Aquia formations, also of Eocene age, which extend all the way to the outcrop of Eocene strata in the vicinity of Annapolis.

Results of a short pumping test on wells penetrating the "400-foot" aquifer indicate a transmissibility of 45,000 gallons a day per foot, and a storage coefficient of 3.7×10^{-4}. Although the data are not necessarily representative of any sizable portion of the aquifer, they are used to compute a tentative maximum pumping rate for a specific distribution of wells at Cambridge.

The report outlines a program of investigations that would be necessary to provide a basis for a reasonably satisfactory estimate of optimum yield.

LOCATION AND PURPOSE

Cambridge is in Dorchester County, Md., about at the center of the Eastern Shore of Maryland (fig. 1). It is a port on the Choptank River, which is a broad estuary tributary to Chesapeake Bay.

The purpose of these notes on the geology and ground-water resources of Cambridge is to clarify the issues and problems connected with the continued production and further development of ground water there. These remarks and records are the result of a brief investigation made during parts of June, July, and August, 1951, by the Geological Survey, United States Department of the Interior, in cooperation with the State of Maryland, Department of Geology, Mines and Water Resources. The investigation is part of a 5-year study of the geology and ground-water resources of the Eastern Shore of Maryland begun in August 1949.

These notes were prepared at the request of the Department of Geology, Mines and Water Resources, as a result of a contest between the Phillips Packing Co. and the Dorchester Water Co., both of Cambridge. The Phillips Co. in June 1951 filed with the Director of the Department of Geology, Mines and Water Resources an application for a permit to take water, under the Maryland Water Resources Law of 1933. The request was for 500,000 gallons a day as a minimum, 2,000,000 gallons a day as an average, and 2,500,000 gallons a day as a seasonal maximum, from a group of wells drilled to the "400-foot" aquifer. The wells are proposed to be located on the Phillips property, about 500 acres in the southeast section and outskirts of Cambridge. The Dorchester Water Co., a private company enfranchised to supply the city of Cambridge, which derives the greatest part of this water from the "400-foot" aquifer, has opposed this request. A preliminary hearing was held July 6, 1951, before the Maryland Commission on Geology, Mines and Water Resources in Latrobe Hall, Johns Hopkins University, Baltimore. At that hearing, the Phillips Co. stated the nature of its request and the Dorchester Water Co. asked for a continuance to permit the preparation of grounds for opposing the request to take water. A second hearing is scheduled for October 17, 1951, at the same place.

Both parties have engaged consultants, and the purpose of this report is to provide background data on geology and hydrology for the information of these consultants, the Commission on Geology, Mines and Water Resources, and the general public.

PREVIOUS REPORTS

The geology and water supply in the immediate vicinity of Cambridge have been described in early reports by Miller (1912) and Clark, Mathews, and Berry (1918, pp. 299-309, 509).1/

1/ See references at end of text.

The water used at Cambridge is derived entirely from the ground. No suitable surface-water sources are known. The water of the Choptank River is brackish.

The population of Cambridge was 10,366 in 1950 (Editor and Publisher, 1951, p. 180). The population in 1951 is estimated by the City Clerk to be 11,000. However, since the end of World War II, in 1945, the suburbs of Cambridge have grown and the water company reports that about one-fourth of its domestic water supply is distributed to homes outside the corporate limits of Cambridge.

The population trend is indicated by the following table (Sixteenth Census of the United States, 1940, p. 464, with 1950 derived from Editor and Publisher, 1951).

Population of Cambridge, Md.

Year	People
1860	1,862
1870	1,642
1880	2,262
1890	4,192
1900	5,747
1910	6,407
1920	7,467
1930	8,544
1940	10,102
1950	10,366

The city of Cambridge is shown on the map, figure 2, which also shows the location of wells. The city is develeped on a smooth terrace whose altitude ranges from sea level to 25 feet above sea level.

The municipal and industrial water of Cambridge is supplied almost exclusively by the Dorchester Water Co. Water is derived from 11 wells, located at 7 stations. These and other wells are shown on the map (fig. 2) and described in the well table at the end of this report.

Records of Water pumped at Cambridge have been kept from 1932 to date and are shown in monthly total in the attached table (Easton, 1936-51; Bixler, 1951). Records prior to 1932 are not available, but an early reference (Clark and others, 1918, p. 309) shows a daily consumption of 400,000 gallons. Remarks in the preface of that report suggest that this rate, amounting to a yearly total of 146 million gallons, might apply to the year 1916. The first well on record tapping the "400-foot" aquifer at Cambridge, drilled in 1888, was reported to yield 100 gallons a minute (Clark and others, 1918, p. 309). If this rate of yield was continuous, the annual yield of the aquifer would have been about 53 million gallons of water.

Pumpage of Dorchester Water Co.
(In millions of gallons)

(Easton, 1936-51; Bixler, 1951)

Month	1932	1933	1934	1935	1936	1937	1938	1939	1940	1941
Jan.	27.0	29.3	26.3	32.9	39.5	42.7	27.9	36.9	39.9	46.1
Feb.	25.8	34.1	44.5	39.5	45.2	46.3	27.8	35.4	40.5	35.6
Mar.	29.5	41.5	49.7	39.3	46.3	59.1	35.6	45.0	40.9	35.6
Apr.	30.1	41.6	34.5	37.6	41.9	41.1	46.5	41.3	45.7	50.2
May	26.4	46.2	30.7	43.1	47.1	47.6	53.2	50.8	43.2	55.7
June	36.6	50.2	47.7	54.5	61.1	55.4	59.8	50.1	57.1	47.1
July	39.9	50.8	52.8	55.7	44.7	49.9	64.0	47.4	58.3	54.6
Aug.	41.2	57.4	59.5	72.0	75.2	76.1	74.1	73.4	78.9	66.0
Sept.	46.1	56.1	63.8	67.3	78.8	52.4	48.8	71.1	56.6	78.4
Oct.	39.7	42.6	64.4	61.0	61.0	46.5	43.3	51.1	59.6	68.0
Nov.	34.5	34.7	43.7	47.7	52.1	51.6	49.4	42.1	46.2	57.4
Dec.	33.9	33.0	42.9	43.6	45.9	37.2	55.6	38.0	45.5	53.7
Total	410.7	517.5	560.5	594.2	638.8	605.9	586.0	582.6	612.4	648.4

Pumpage of Dorchester Water Co.--Continued
(In millions of gallons)

Month	1942	1943	1944	1945	1946	1947	1948	1/	1949	1/	1950	1/	1951	1/
Jan.	48.7	78.3	75.0	75.0	87.2	76.4	67.3	0	59.7	0	52.9	0	56.9	15.3
Feb.	48.8	52.2	74.7	66.3	71.7	69.6	69.0	0	52.5	0	50.2	0	51.2	13.9
Mar.	42.9	40.2	77.6	71.1	66.6	75.5	69.8	0	57.4	0	50.0	0	60.8	15.0
Apr.	51.4	41.5	68.2	71.3	70.0	71.7	60.0	0	62.0	0	53.7	0	55.8	13.6
May	45.2	51.1	68.8	66.1	67.1	72.1	73.2	0	68.5	0	68.9	0	60.2	13.5
June	59.6	71.5	74.4	73.4	75.2	76.9	87.1	0.3	91.3	3.4	84.9	8.5	79.6	13.1
July	59.7	79.0	68.0	78.7	73.1	78.2	83.4	0	91.0	2.8	78.9	14.5	89.5	5.0
Aug.	77.7	97.0	95.9	91.7	115.7	111.7	96.6	3.0	107.2	1.6	110.2	12.5		
Sept.	77.3	82.6	89.3	90.2	102.2	113.3	90.8	2.9	84.8	0	92.3	13.4		
Oct.	59.1	64.6	78.0	86.9	92.6	72.7	73.4	1.9	79.9	0.1	74.6	14.6		
Nov.	60.2	66.4	75.9	87.2	88.8	56.8	69.2	2.5	57.8	0	58.0	14.2		
Dec.	60.2	72.7	79.4	101.1	83.4	61.5	71.8	0.3	52.1	0	50.4	12.9		
Total	690.8	797.1	925.2	959.0	993.6	936.4	911.6	10.9	864.2	7.9	825.0	90.6		

1/ Water produced from the deep "950-foot" aquifer, through well Dor-Ce 3, Dorchester Ave. no. 2. All other wells produce from the "400-foot" aquifer.

The Phillips Packing Co. is the chief industry of Cambridge. The company has used a large proportion of the water produced at Cambridge for many years. The consumption from 1931 to date (included in the figures given in the preceding table for the Dorchester Water Co.) is shown in tabular form on the next two pages (Tall, 1938-51; Easton, 1931-37).

Two aquifers provide all the water currently used at Cambridge: the "400-foot" aquifer and the "950-foot" aquifer. The "400-foot" aquifer is the major water producer, having yielded an estimated 21 billion gallons of water at Cambridge in the 63 years since the first well was drilled in 1888, half of it in the last 14 years. The "400-foot" aquifer has been yielding about 900 million gallons a year in recent years. The "950-foot" aquifer is a minor water producer, which has been pumped at rates of 70 to 210 million gallons a year since it was first penetrated in 1945 for production in the Cambridge area.

Water consumption of Phillips Packing Co.
(In millions of gallons)

(Tall, 1938-51; Easton, 1931-37)

Month	1931	1932	1933 1/	1934	1935	1936 1/	1937 1/	1938	1939	1940
Jan.								6.2	11.3	8.6
Feb.								7.7	11.5	11.1
Mar.			31			38	54	10.7	17.1	11.3
Apr.								18.5	16.2	21.1
May								35.2	21.6	17.1
June			65			68	55	16.6	17.1	23.9
July								25.9	17.6	24.0
Aug.								48.7	38.1	50.3
Sept.			72			139	80	11.6	42.0	31.7
Oct.								18.2	24.8	34.9
Nov.								21.2	17.9	25.3
Dec.			45			81	58	20.3	14.1	14.8
Total	57	151	213	248	289	326	246	240.8	249.3	274.1

1/ Quarterly consumption given at the end of each 3 months.

Water consumption of Phillips Packing Co.--Continued
(In millions of gallons)

Month	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951
Jan.	20.1	18.3	36.6	38.5	35.0	50.4 1/ 59.4	31.2	16.4	14.8	12.9	30.8
Feb.	12.1	20.4	14.9	37.7	31.6	34.2	24.8	17.9	13.7	14.6	26.0
Mar.	6.7	11.6	10.2	38.5	33.9	41.4 1/ 50.4	27.6	17.3	17.4	10.3	34.3
Apr.	24.4	20.6	11.8	42.4	35.4	38.9	27.3	10.5	22.9	15.5	28.4
May	21.2	20.2	19.3	26.8	31.5	17.1	22.4	19.3	24.9	24.3	29.5
June	18.9	14.7	28.7	27.6	38.6	34.4	25.9	31.3	41.3	39.8	43.4
July	24.1	22.6	36.6	20.6	44.7	28.6	26.6	25.4	40.6	26.9	40.4
Aug.	33.5	39.9	40.2	46.3	37.3	60.9	69.5	42.9	57.6	65.8	
Sept.	49.5	42.8	37.0 1/ 40.2	52.2	61.4	53.3	53.4 1/ 63.4	43.3	45.6	57.8	
Oct.	40.7	24.3	27.8	37.2	32.6	44.7	19.2	27.6	41.6	43.6	
Nov.	30.7	24.0	29.6	45.9	47.5	51.3	13.7	24.4	25.5	31.1	
Dec.	24.6	21.8	31.4	42.9	45.4	42.7	18.0 1/ 8.0	27.0	14.0	22.6	
Total	306.5	281.2	324.1 1/ 327.3	456.6	474.9	496.9 1/ 515.9	359.6	303.3	359.9	365.2	7-month total 232.5

1/ Reported by N. Easton, Dorchester Water Co.

The major aquifer is called the "400-foot" aquifer by drillers and others in the Cambridge area, because it is encountered about 360 feet below the land surface, and wells customarily penetrate the sand about 40 feet. The sand is 119 feet thick in the water company's deep well (no. 2) on Dorchester Avenue (well Dor-Ce 3), 100 feet thick in the deep well of the Crystal Ice and Cold Storage Co. on Trenton Street (Dor-Ce 15), and 151 feet thick in the deep well of the Crystal Ice Co. on Washington Street (Dor-Ce 1).

The minor aquifer is called the "950-foot" aquifer in this report because it is encountered at about that depth in wells Dor-Ce 1, Dor-Ce 3, and Dor-Ce 15. The sand is 31½ feet thick in well Dor-Ce 1; 31 feet thick in Dor-Ce 3; and 38½ feet thick in Dor-Ce 15. Well Dor-Ce 3, public supply well 2 on Dorchester Avenue, produces 330 gallons a minute and is operated almost continuously. The driller reports that this well was difficult to develop, and even today it produces a fine silt for the first hour after it is turned on. During this time the discharge is wasted until the water clears.

The chemical quality of water from both aquifers is excellent and very similar, as shown in the adjacent table. The waters are of the sodium bicarbonate type, soft, low in chloride, slightly alkaline, low in iron, and containing just the right amount of fluoride considered desirable for reducing tooth decay in children. The water of the "950-foot" aquifer is slightly better for making ice than the water of the "400-foot" aquifer because it has less bicarbonate and gives off less carbon dioxide, and therefore makes a clearer ice.

The temperature of water from the "400-foot" aquifer was 63.5° F. in well Dor-Ce 2, and that of the "950-aquifer" was 71.5° F. in well Dor-Ce 3, both on Dorchester Avenue, on October 8, 1948. Artesian aquifers are not known to vary much in temperature the year around, nor from year to year. On the above basis, the geothermal gradient is then about 1.3° F. for each 100 feet of depth between these aquifers.

Analyses of ground waters at Cambridge

Wells of Dorchester Water Co. at Dorchester Avenue

(Parts per million)

Well no.	Depth (feet)	Dissolved solids	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Carbonate (CO_3)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Total hardness as $CaCO_3$	pH
Dor-Ce 2	412	473	20	0.11	5.1	3.5	172	6.4	8	455	19	7.5	1.2	0.4	27	8.0
Dor-Ce 3	977	385	18	.22	3.2	2.4	139	5.3	9	376	14	6.8	1.0	.2	18	8.2

Samples collected October 8, 1948, by R. R. Meyer and Gerald Meyer.
Analyzed by E. W. Lohr, Quality of Water Branch, Water Resources Division, Geological Survey, U. S. Department of the Interior.

A third water-bearing sand has been tapped in the past. This sand is reported by Norman M. Shannahan, well driller of St. Michaels, to be the water source for two unused wells at the Phillips Packing Co., Dor-Ce 16 and Dor-Ce 17, which he drilled in 1903 to a depth of 293 feet, and which he recently stated might yield as much as 150 gallons a minute each. This sand is shown on the log of Dor-Ce 3, Dorchester Avenue public-supply well no. 2, to be 20 feet thick, lying between 280 and 300 feet below the land surface. Samples from well Dor-Ce 2 indicate that it is a gray medium-grained quartz sand, fairly well sorted. The sand appears on logs of wells from the southeastern section of Cambridge but is not shown on logs of wells drilled in other sections of the city. McCoy Tall, plant engineer, Phillips Packing Co., measured the water level of Dor-Ce 16 on May 25, 1951, as 50 feet below the land surface. Mr. Shannahan reports that this represents a loss of 34 feet since the well was drilled. No wells in this aquifer are known to have produced for many years; consequently, the water level, if substantially lower than formerly as reported, would seem to indicate that the sediments between the shallower sand and the "400-foot" aquifer are slightly permeable and that the shallower aquifer has lost water to the deeper. There is no other apparent reason for a decline of head below sea level.

Small quantities of water are obtained from a few dug wells remaining in the older section of the city. These wells are in general 3 to 5 feet in diameter and less than 20 feet deep. Wells Dor-Ce 23, 24, 25, and 26 in the table represent almost all the remaining dug wells in the area. It is reported that several drive-point wells were put down in the Cambridge area a number of years ago but were not successful. None were found in the well canvass.

In summary, only two aquifers now producing are known beneath Cambridge: the "400-foot" and the "950-foot" sands. Well Dor-Ce 3 was originally drilled to a depth of 977 feet, and this is the deepest hole known in the Cambridge area. Information on the water sands is based on driller's logs. It is possible that electrical or radioactive logs would show the presence of other sands; however, because several reliable drillers have operated in the area, it is probable that any undiscovered sands above 977 feet would be thin and not highly productive.

It is also possible that deeper productive sands, below 977 feet, could be reached at Cambridge. Such sands have been penetrated at Easton and at Crisfield, but were not found in a 1,245-foot hole at Trappe. The quality of the deeper waters is uncertain. The deep water at Easton is good; that at Crisfield is not so good.

GEOLOGIC SECTION AT CAMBRIDGE [1/]

The geologic section at Cambridge is illustrated in figure 3. The descriptions of the general character of the sediments are based upon various reports describing the regional geology of the coastal plain of Maryland and Delaware, the combined work of many geologists on the surface outcrops, and studies of well samples and logs. The graphic log of the deep well, Dor-Ce 3, the Dorchester Water Co.'s Dorchester Avenue well 2, is based upon (1) the driller's log (open file, Shannahan, 1946, permit 174), (2) microfossil correlation by Miss Elaine Shifflett (1948, p. 25 and fig. 21), who identified the contacts between the rocks of Jackson age and the Pamunkey group, between the Pamunkey and the Paleocene, and between the Paleocene and the upper Cretaceous in well Dor-Ce 3, and (3) lithologic determination of the top of the Eocene at a depth of 366 feet by the authors, on the basis of the first appearance of glauconite.

Drillers report that they have encountered at least two hard layers, between which is a sandy zone 10 to 20 feet thick, when they drill to the "400-foot" aquifer at Cambridge. Water from the sandy zone is described as carrying a fine silt (diatomaceous earth?), so the drillers case off this upper sand and set casing on the second hard layer.

1/ The geologic nomenclature and classification of this report have not been checked by the U. S. Geological Survey.

Careful study of the samples of well Dor-Ce 2, on Dorchester Avenue, confirms this interpretation. From 300 to 349 feet a light-gray fine-grained silt and clay (diatomaceous) is present. The samples from 349 to 364 feet are a mixture of gray well-sorted fine-grained quartz sand and gray silt (diatomaceous) with a few shell fragments. A bed "hard as bedrock" occurs at 364 to 364½ feet. From 365 to 412 feet, the bottom of this hole, the sand is a salt-and-pepper fine- to coarse-grained quartz sand. A few grains of glauconite appear in the first sample of this series, 365 to 368 feet, and the mineral becomes increasingly abundant in succeeding samples, up to 10 percent of the grains. Many fragments ranging in size from grit to fine pebbles occur with this sand, and suggest alternate layers of rock and fine sand.

The presence of hard beds is confirmed also by the drillers' reports, which describe alternate beds of hard and free sand. At least one driller states that open holes are as productive as screened wells in this sand. This claim is, in part, substantiated by the two wells at Washington Street, Dor-Ce 4 and Dor-Ce 5, which were completed in 1931 with an open hole from 365 to 405 feet, and which produced a reported 1,500 gallons a minute together. The wells have been recased but they still produce from an open hole, and they yielded a total of 1,160 gallons a minute during a 1-hour test on July 3, 1951.

The sandy zone between 349 and 366 feet is correlated by the writers as the basal part of the Calvert formation, equivalent to the Fairhaven diatomaceous earth member of that formation in Anne Arundel County (Shattuck, 1904, p. lxxii; Overbeck, 1951, p. 25; Dryden and Overbeck, 1948, p. 53).

The beginning of the salt-and-pepper, slightly glauconitic quartz sand found at 366 feet in wells Dor-Ce 2 and Dor-Ce 3 on Dorchester Avenue is believed to be the top of the rocks of Jackson age. Miss Shifflett notes that Jackson foraminifera are not encountered above 450 feet in samples from well Dor-Ce 3 (1948, p. 26), but that the contact should be drawn at a higher level on the basis of lithology.

The discussion of the correlation of the "400-foot" aquifer may seem at first glance to be a geological determination, of little practical value. On the contrary, it is of great importance in establishing a basis for regional study of the extent, thickness, and structure of this aquifer.

The Eocene formations of Maryland are, in general, highly productive of water. The "400-foot" aquifer at Cambridge is principally, if not entirely, in the uppermost and youngest Eocene sediments, those of Jackson age. Sediments of Jackson age are widespread along the Coastal Plain from the Gulf Coast of Texas to Maryland, but have not yet been recognized in Delaware or New Jersey.

The sediments of Jackson age do not crop out in Maryland but are known from wells in St. Marys, Calvert, Dorchester, Somerset, Wicomico, and Worcester Counties. Not all the sediments consist of sand; indeed, the lower 105 feet of the formation, in well Dor-Ce 3, from 485 to 590 feet, has been logged as a clay. Even the sand of the "400-foot" aquifer gives place eventually to silt and clay at unknown distances south and east of Cambridge, but somewhere within the 36 miles to the Hammond oil test, 6 miles east of Salisbury (Anderson, 1948, p. 17). North and northwest of Cambridge the "400-foot" aquifer is present and productive at Trappe but is absent at Easton and has not been recognized at Oxford.

Apparently the line shown on the map, figure 1, in lower Calvert County, showing the northwestern limit of sediments of Jackson age, may be extended across the bay to southern Talbot County. Along this line the sediments of Jackson age wedge out between the formation below the Nanjemoy or Aquia and the Calvert formation above.

Does this line, which lies only 6 miles northwest of Cambridge, represent a hydrologic boundary? Not necessarily. The Nanjemoy and Aquia formations have productive sands also, some of which may be in contact with those of the sediments of Jackson age, so that water may be able to move across the stratigraphic boundary. Such sands in the Nanjemoy and/or Aquia have been identified in well logs from Trappe Station, Royal Oak, St. Michaels, McDaniel, and Kent Island. It thus appears that there is probably a hydrologic connection through successive sands, gradually rising, from the "400-foot" aquifer at Cambridge, all the way to the outcrop at Annapolis, Love Point, and Rock Hall and possibly along the strike on the north to Chestertown, and on the west to the Patuxent River.

That such a group of overlapping sands forms a continuous sheet is unlikely. Rather, there are probably areas where shale predominates through most of the Eocene section, representing "islands" of low permeability, around which the ground water moves in the more permeable sand-reservoir channels. The delineation of the more permeable "channels" and the less permeable "islands" is a major task in the study of Eocene stratigraphy and in obtaining a thorough understanding of the hydrology of the "400-foot" aquifer.

It may be remarked that the outcrop of the Eocene crosses Chesapeake Bay. When it is recalled that the water of the bay is generally brackish, it is well to consider whether the salt water may enter the aquifers along this zone and eventually contaminate the wells down the hydraulic gradient, including those at Cambridge. Such an occurrence is a possibility - a possibility that, if it exists, would be hastened by excessive pumping in any area down dip.

The new bridge over Chesapeake Bay from Sandy Point to Kent Island is constructed on the outcrop of the Eocene. Borings for pier foundations have been made all across the bay and show the geologic section there (Greiner, 1943, pl. 6). Beneath the bay the Eocene is blanketed by 15 to 130 feet of Recent and Pleistocene deposits, two-thirds of which are silt and clay. This blanket decreases the opportunity for salt-water encroachment but does not rule it out. Such encroachment, however, doubtless could be detected in wells far up dip long before it reaches the Cambridge area.

The extent and structure of the "400-foot" aquifer are very incompletely known, but perhaps a sketchy resume' might indicate the scope of the problem. As mentioned earlier, the sediments of Jackson age, which have been identified as including the "400-foot" aquifer at Cambridge, apparently do not appear in outcrop, but thin out along a line about 6 miles northwest of Cambridge. They may be hydraulically connected to other Eocene sands, of the Nanjemoy and Aquia formations, northwest of that line. The rate of dip on the top of the Eocene from the outcrop to Cambridge is 11 feet to the mile. The general direction of dip is southeast. The strike is northeast.

To the south the "400-foot" aquifer has been traced in graphic well logs as far as Bishops Head at the southern end of Dorchester County; according to Shifflett (1948, p. 20) it is present at Smith Island in the Bradshaw well, where it is 90 feet thick; and according to McLean (1950, p. 136) it is present at depths of 760 to 860 feet as a 100-foot sand at Crisfield 44 miles south of Cambridge. To the east the sand has not been traced beyond Chateau Church, about 5 miles from Cambridge, because records of wells are not available. Near Salisbury the sediments of Jackson age are present but appear chiefly as clay (Anderson, 1948, p. 17). To the northeast the sand has been traced as far as Secretary, and it may underlie Hurlock and Federalsburg, but correlation has not yet been established. To the southwest it has been traced to Mundy Point, Northumberland County, Va. (Bennett, 1951), 47 miles from Cambridge.

The top of the sand of Jackson age dips 9 feet to the mile from Cambridge to Crisfield. The top of the sediments of Jackson age dips 20 feet to the mile from Cambridge to Salisbury, and this is probably near the true dip.

The "400-foot" aquifer is an artesian sand, sandwiched between confining layers of silt and clay. According to Clark and others (1918, p. 303) the first wells in this vicinity were drilled in 1888. Their report says, "the first wells sunk had good flows, but since the addition of so many wells in later years, the flows have ceased and the water now stands a few feet below sea level."

Some idea of the decline in water level in the area from 1936 to 1945 can be obtained from figure 4, which shows water levels in a public-supply well at Cambridge for that period. The trend line shows a drop from 45 feet to 120 feet below the land surface in 15 years from 1931 to 1945 (miscellaneous measurements made in 1931 when the wells were drilled are noted on the graph). The drop has not been regular, but it has averaged 5 feet a year over this period. The pumpage during this period has increased from 400 million gallons a year to more than 900 million gallons a year.

An artesian sand acts both as a storage reservoir and as a conduit. From the moment the first well begins to discharge, some water is obtained from storage and some water is transmitted via the minute "pipes" between the sand grains from points at increasing distances from the well. The water from storage comes from compaction of the aquifer and associated beds in the vicinity of the pumped well - especially the compaction of silt and clay layers, and from the expansion of water due to the relief of pressure. The water from other areas comes, in the last analysis, from recharge. Recharge may take place in the intake area of an artesian sand where it crops out. There the rain that falls and seeps in, and under some conditions the rivers that leak water through their beds, provide recharge for the artesian sand.

The beds overlying an artesian sand may not be watertight. If water pressure in the sand is, or is drawn, lower than water pressure in the overlying silts and clays, some recharge may be obtained by leakage through those beds from permeable beds above. Likewise, recharge may occur by leakage from below, if underlying confining layers lie above beds containing water under higher pressure.

The outcrop of the Eocene is as high as 200 feet above sea level in Charles County on the Western Shore, and 60 feet above sea level in Kent County on the Eastern Shore. Infiltrating precipitation reaches a water table about 180 feet above sea level in Charles County and 50 feet above sea level in Kent County. These high water levels may have provided the hydraulic drive for wells to flow in the early days, and now provide the hydraulic drive for recharge to heavily pumped areas.

The rate of recharge depends, among other factors, upon the transmissibility of the aquifer. Transmissibility, T, is a product of the permeability, P, and the saturated thickness, m.

$$T = Pm$$

The permeability expresses the ability of the material constituting the aquifer to permit water to percolate through it under pressure. The transmissibility, T, of a formation obviously varies from place to place, as the thickness and permeability vary. The storage, S, likewise varies with the thickness and lithology of the aquifer and associated strata.

Transmissibility, T, and storage, S, are often called formation constants, and they can be determined locally by means of the measurement of the drawdown and recovery of water levels in observation wells in response to known rates, Q, for periods of time, t, of pumping of a production well (Theis, 1935; Wenzel, 1942).

If the formation constants can be determined, a basis is established for predicting future drawdown of water level, s, at given radial distances, r, from pumped wells, Q_1, Q_2, ... Q_n, at times, t_1, t_2, ... t_n. These predictions are limited by the extent to which the formation constants remain the same, both with time and with distance, or change at known rates and in a way permitting mathematical analysis.

A well-field test was run on the "400-foot" aquifer on July 23, 1951. Because it was impractical to shut down all wells in the well field to allow the water level to recover, the two wells at Well Field, Dor-Ce 12 and Dor-Ce 13, the well on High Street, Dor-Ce 9, and the well on Mill Street, Dor-Ce 10, were pumped at a steady rate continuously for 64 hours prior to the test and all during the test. (See fig. 2.) The Trenton Street wells, Dor-Ce 7 and Dor-Ce 8, were not operated during this time and had not been operated during the previous month. The Fletcher Street well, Dor-Ce 6, was not operated for 64 hours prior to the test, nor during the test. The Washington Street wells, Dor-Ce 4 and Dor-Ce 5, were not operated for a week before the test and Dor-Ce 5 was not operated during the test.

The Washington Street well 1, Dor-Ce 4, was used as an observation well, and an automatic water-stage recorder was placed upon it 11 days prior to the test, and operated during the test. Dorchester Avenue well 1, Dor-Ce 2, was selected for the pumped well. It was shut off 64 hours before the test started. The water level recovered to a depth of 99.58 feet below the land-surface datum by the start of the test, and it was assumed that it would not have changed further if well Dor-Ce 2 had not been pumped. This assumption is not strictly true, but the probable deviation of the water level, as shown by the 11-day record obtained before the test, would not affect the results of the test, as computed, by more than a few percent - a negligible quantity in such computations. The observation well was at a distance $r = 1,171$ feet from the pumped well. At 8:15 a. m. on July 23 the test started. Well Dor-Ce 2 was pumped at the rate of 637 ± 10 gallons a minute for 8 hours 45 minutes, and then shut off. Recovery levels were measured for 1 hour 40 minutes. The drawdown and recovery water levels are shown in the following table.

Drawdown and recovery of water level in Washington Street well 1 (Dor-Ce 4) due to the pumping of Dorchester Avenue well 1 (Dor-Ce 2), July 23, 1951

Drawdown

Time	Time since pumping started, in minutes	Water level 1/
8:15 a.m.	0	99.58
:19	4	.59
:22	7	.60
:24	9	.61
:26	11	.62
:28	13	.64
:30	15	.67
:32	17	.69
:34	19	.72
:37	22	.77
:40	25	.82
:45	30	.91
:50	35	100.00
:55	40	.10
9:00	45	.19
:05	50	.29
:10	55	.38
:15	60	.48
:20	65	.56
:25	70	.65
:30	75	.74
:35	80	.83
:40	85	.91
:45	90	.99
10:00	105	101.23
:15	120	.45
:30	135	.65
:46	151	.86
11:00	165	102.03
:17	182	.22
:35	200	.42
:55	220	.62
12:15 p.m.	240	.80
:45	270	103.06
1:25	310	.38
:45	330	.48
2:00	345	.59
:15	360	.72
:30	375	.82
:45	390	.91
3:00	405	104.00
:15	420	.09
:30	435	.16
:45	450	-
4:30	495	.46
:45	505	.53
5:00	520	.58

Recovery

Time	Time since pumping stopped, in minutes	Water level	Recovery 2/ (increment in feet)
5:00 p.m.	0		
:04	4	104.59	0.01
:06	6	.60	.00
:12	12	.59	.03
:15	15	.57	.06
:17	17	.55	.09
:19	19	.53	.12
:21	21	.51	.15
:23	23	.48	.19
:25	25	.46	.21
:27	27	.43	.25
:30	30	.39	.30
:33	33	.35	.35
:36	36	.30	.41
:39	39	.26	.46
:42	42	.22	.51
:45	45	.17	.57
:50	50	.10	.65
:55	55	.04	.73
6:00	60	103.96	.82
:10	70	.82	1.01
:20	80	.70	1.16
:30	90	.57	1.32
:40	100	.45	1.48

1/ Water levels are given in feet below measuring point (top of casing), which is about 0.75 foot above land surface.

2/ Recovery increments are the differences between the observed water level and the extrapolated drawdown.

A graph of drawdown and recovery water levels, plotted against time on log-log scales, was compared to the type curve (Wenzel, 1942, pp. 87-89). The early part of the drawdown curve was selected for comparison, because that part is least likely to be affected by extraneous influences, such as an extrapolation of the prepumping hydrograph different from that assumed (as discussed in the last paragraph), such as fluctuations caused by changes in atmospheric pressure, or such as the presence of boundaries. The curve for the recovery period, which was shorter than the drawdown period, appeared not to show such disturbances, and checked well with the early part of the drawdown curve. The computed values are:

Drawdown	Recovery
T = 47,500 gallons a day per foot	T = 42,500 gallons a day per foot
$S = 3.6 \times 10^{-4}$	$S = 3.8 \times 10^{-4}$

Average

T = 45,000 gallons a day per foot

$S = 3.7 \times 10^{-4}$

Thus, the portions of the curves selected for the computation showed that the behavior of the water levels was as if the aquifer were unlimited in extent, and as if the recharge, other discharge, transmissibility, and storage were constant.

How well these transmissibility and storage coefficients represent the actual conditions can be tested by comparing water levels calculated from theory with those actually determined in practice.

Fortunately there is an old well 2 miles northwest of the general center of pumping, which is about at Fletcher Ave. Station IV, Dor-Ce 6. The water level in the old well when it was drilled (1904) was recorded as 3 feet above land surface (Clark and others, 1918, p. 309, well 14). This well has been identified as the Slagle well, Dor-Bd 2, and the water level was measured as 66.90 feet below the measuring point, which is 2.4 feet above land surface, on July 18, 1951. The water level thus has declined about 68 feet in 47 years. This well has been fitted with an automatic water-stage recorder in order to register future changes.

From a topographic map, and examination of the site in relation to the nearby beach, it is estimated that the land surface at the well is 3 feet above sea level, thus the present water level is about 65 feet below sea level.

In order to compute what the water level should be, in this well, at present, under the constants and assumptions of the well-field test, it is necessary to generalize the pumping estimates and records over the years from 1888 to June 30, 1951, into several step increments. These increments, and the drawdown in water level due to each increment, as determined from the Theis chart (1939) are shown in the following table.

Drawdown at a distance of 2 miles due to successive pumpage increments at Cambridge ("400-foot" aquifer, T = 45,000 gpd/ft. S = 0.00037)

Pumpage increment			Time			$\frac{Q}{T}$	Chart factor	Drawdown
	Mil. gals. a year	Q (gpm)	Period to June 30, 1951	Years	Days		Kp	(feet)
Q_1	120	228	1888	$63\frac{1}{2}$	23,180	0.00507	1,030	5.22
Q_2	180	342	1916	$25\frac{1}{2}$	9,310	.00760	920	6.99
Q_3	260	494	1932	$19\frac{1}{2}$	7,120	.01099	894	9.82
Q_4	70	133	1935	$16\frac{1}{2}$	6,020	.00295	879	2.59
Q_5	310	589	1942	$9\frac{1}{2}$	3,470	.01305	820	10.70
	940	1,786						35.32

A comparison of the cumulative drawdown of 35 feet in $63\frac{1}{2}$ years, obtained from theoretical considerations, with an actual drawdown of 68 feet in 47 years, indicates (1) that the average transmissibility and/or storage of the formation is lower than the values obtained in the well-field test, or (2) that there are boundaries within significant distances which have definitely prevented the well field from obtaining full recharge or storage water from a cone of depression expanding at the theoretical rate.

One such boundary may be the outcrop area, beyond which the Eocene formations cease to exist. The effect of this boundary, however, is not known. It might behave as an impermeable boundary; the formations beyond it might be such that it would behave as a line of no change in recharge, that is, as no boundary at all; or it might be considered a line of unlimited recharge, that is, a line along which a constant water level would be maintained and along which the rate of recharge would increase in proportion to the drawdown caused by pumping at Cambridge.

That the outcrop area is now rejecting recharge is manifest in springs and seeps in the picturesque valleys from Annapolis to Washington. Whether a portion of this rejected recharge is recoverable, or could be diverted to movement down dip, is speculative, and the matter might not be of practical significance for many years.

The magnitude of the effect of the outcrop boundary can be roughly calculated from the constants and assumptions made in the test, as shown in the following table. Because the outcrop boundary lies about 40 miles from Cambridge, the effect of this boundary can be determined by placing an image well field at 80 miles (Muskat, 1937, pp. 175-181), and postulating that this image well field is being pumped, or recharged, at the same rates as the well field is being pumped at Cambridge.

The image well field could be assumed to be a recharge well field, providing recharge in proportion to the drawdown caused by pumping at Cambridge, simulating a recharge boundary in the vicinity of Annapolis. Or the image well field could be assumed to be a discharge well field, which would result in the establishment of a hydraulic divide in the vicinity of Annapolis that would have the same effect as an impermeable boundary there. A recharge well field would reduce the theoretical $63\frac{1}{2}$-year decline in water level by 3 feet, so that it would only be 32 feet, instead of 35 feet. A discharge well field would increase the drawdown by 3 feet, causing it to be 38 feet instead of 35 feet.

Theoretical effect of an image well field, 80 miles NW. of Cambridge pumping (or recharging) at the same rate as the well field of Cambridge, upon the water level in an observation well 2 miles NW. of Cambridge.
("400-foot" aquifer, T = 45,000 gpd/ft. S = 0.00037)

Pumpage increment			Time				Chart factor	Drawdown (or recovery) due to image well field
	Mil. gals. a year	Q (gpm)	Period to June 30, 1951	Years	Days	$\frac{Q}{T}$	(Ki)	(feet)
Q_1	120	228	1886	$63\frac{1}{2}$	23,180	0.00507	190	0.96
Q_2	180	342	1916	$25\frac{1}{2}$	9,310	.00760	110	.83
Q_3	260	494	1932	$19\frac{1}{2}$	7,120	.01099	85	.93
Q_4	70	133	1935	$16\frac{1}{2}$	6,020	.00295	80	.23
Q_5	310	589	1942	$9\frac{1}{2}$	3,470	.01305	40	.52
	940	1,786						3.47

Although this calculation is based upon the general assumptions of the well-field test, and therefore may not be precise, it does show that the change of water level due to a boundary at 40 miles, whether a recharge or a discharge boundary, is small, and certainly not enough to account for the discrepancy between an observed decline of 68 feet and a theoretical decline between 32 and 38 feet. Therefore, closer boundaries, or lower average values of T and S, must be responsible. It should be pointed out that these computations assume an aquifer extending indefinitely down dip, whereas existing well records show that an impermeable boundary probably exists to the east and south at distances of not more than a few tens of miles. Such a boundary would have an effect of the same order of magnitude as an impermeable boundary 40 miles up dip - still not enough to account for the discrepancy.

In order to give the reader an approximate idea of the performance of the Cambridge aquifer, and to emphasize how incomplete our knowledge is, let us consider the performance under both unfavorable and favorable conditions, such as could be assumed on the basis of our present understanding.

The least favorable conditions would be those caused by the presence of geologic boundaries within short distances. For example, let it be assumed that the "400-foot" aquifer ends along a line 6 miles northwest of Cambridge, where sediments of Jackson age apparently pinch out, as shown by the dashed line with question marks on figure 1. Because, also, the "400-foot" sand of Cambridge is represented by a shale in the deep oil test near Salisbury, let it be assumed that another impermeable boundary lies between Cambridge and Salisbury. The nearest this boundary can be placed is shown by the logs of two wells in the "400-foot" aquifer, one at Secretary and the other at Elliott; both wells show permeable sections in the sediments of Jackson age. This line also lies 6 miles from Cambridge, but east-southeast therefrom, as shown by a second questioned dashed line on figure 1. No other boundaries need be assumed because the aquifer has been correlated in wells as far as the banks of the Potomac River, in Westmoreland and Northumberland Counties, Va., 47 miles southwest of Cambridge. It apparently shales out between there and Yorktown, Va., 97 miles south of Cambridge, where the Chickahominy formation of Jackson age, is described as a blue and gray clay (Cederstrom and Cushman, 1945, pp. 2-3). It is assumed that a boundary at such a great distance from Cambridge would have a negligible effect on the water levels there.

The wedge formed by these two assumed impermeable boundaries, as shown on the map, figure 1, forming an angle of 60 degrees, is not believed to exist as such in nature, but is used merely to limit the aquifer to permit rational mathematical treatment. The pumping of the wells at Cambridge, in their successive increments from 1888 to the present, would be reflected by image wells assumed to be an equal distance from the impermeable boundaries on either side of Cambridge. These primary image well fields would inspire secondary image well fields across the opposite boundary, until, in all, the pumped well field at Cambridge would create six images (two of them superimposed), which would increase the drawdown at Cambridge several fold. The effect of these images has been calculated and is given in the following table.

Theoretical effect of two impermeable boundaries one 6 miles NW, the other 6 miles ESE, of Cambridge, upon water levels in an observation well 2 miles NW of Cambridge.

Increment	Rate (gpm)	Time: Period to June 30, 1951	Time: Years	Time: Days	Drawdown due to pumped well and images (feet)
Q_1	228	1888	$63\frac{1}{2}$	23,180	18.72
Q_2	342	1916	$25\frac{1}{2}$	9,310	23.57
Q_3	494	1932	$19\frac{1}{2}$	7,120	32.06
Q_4	133	1935	$16\frac{1}{2}$	6,020	8.31
Q_5	589	1942	$9\frac{1}{2}$	3,470	31.31
	1,786				113.97

That this calculated drawdown, based on T = 45,000 gallons a day per foot, and $S = 3.7 \times 10^{-4}$, and on the two boundaries 6 miles away, is so much greater than the observed drawdown in Dor-Bd 2 (68 feet) suggests that one or both of these boundaries, so chosen, is too close or does not exist, that recharge may be coming through leaky confining beds above or below, or that the actual values of T and S are larger than the computed values.

At any rate, these are the closest boundaries that can be drawn on the basis of present knowledge, and they appear to represent the least favorable assumption that is justified.

Under these unfavorable assumptions it would seem desirable to project the present rate of pumping 50 years into the future, to determine what the total drawdown would be then.

Theoretical drawdown due to pumping at the present rate with the same two impermeable boundaries 6 miles NW. and 6 miles ESE., of water level in an observation well 2 miles NW. of Cambridge.

Increment	Rate (gpm)	Time			Drawdown (feet)
		Period to June 30, 2001	Years	Days	
Q_1	228	1888	113½	41,300	20.89
Q_2	342	1916	75½	27,560	28.75
Q_3	494	1932	69½	25,370	40.86
Q_4	133	1935	66½	24,270	10.92
Q_5	589	1942	59½	21,720	47.42
	1,786				148.84

Thus in 50 years of additional pumping at the present average rate of 1,786 gallons a minute, the drawdown would increase only 34.87 feet (148.84 - 113.97) in this observation well. If this 35 feet be added to the present level of 65 feet below sea level, we might reasonably expect, under the least favorable assumptions, that the water level would be 100 feet below sea level in this observation well, 2 miles from the center of pumping.

Now, it may be asked, what additional increment, Q_6, could be imposed upon the "400-foot" aquifer, at a site, for example, 1 mile southeast of the present center of pumping. The additional increment should be one at which the formation could be pumped for a reasonable period of time, sufficient to amortize most of the investment in well-field equipment. Let us assume a period of 50 years.

Under the impact of the new pumping, even with a locus a mile away, the cone of depression would be deepened further within the Cambridge area. This is natural and necessary to establish sufficient hydraulic gradient to transmit the additional water to the area.

It would be reasonable to choose an additional decline in water level to 350 feet below sea level in the central area, for at this depth the producing sands would begin to be dewatered, and the transmissibility would be reduced although the storage coefficient would be increased. This is not to say that pumping could not continue after this time but that a new regimen of pumping, at reduced rates from a larger number of wells, would be necessary.

At present, the pumping levels are about 160 feet below sea level in the Dorchester Water Co. wells; that is, they are about 95 feet below the water level in Dor-Bd 2, 2 miles northwest. At increased rates of pumpage this difference in water level would be greater. Let it be assumed that the water level in Dor-Bd 2 would be allowed to fall to 250 feet below sea level, at which time the pumping levels in the central area would be more than 350 feet below sea level, and the sand would be in the process of being dewatered.

In other words, it is desirable to find the increment rate of pumping, Q_6, that could be undertaken 1 mile southeast of the present center of pumping, during the next 50 years, under the formation constants obtained in the test, assuming the least favorable geologic conditions - that is, two nearby impermeable boundaries, one 6 miles northwest and the other 6 miles east-southeast of Cambridge. Inasmuch as it has already been shown under these assumptions that the water level in Dor-Bd 2 would decline to 100 feet below sea level at the present rate of pumping, 1,786 gallons a minute, in 50 years, it is apparent that we wish to calculate the increment, Q_6, that would cause an additional drop of 150 feet to 250 feet below sea level, in that time. This calculation is summarized in the following table.

Calculation of additional rate of pumping, Q_6 = 2,000 gallons a minute, which could be imposed on "400-foot" aquifer at a new site 1 mile SE. of present city wells, to achieve a drop of 150 feet in 50 years in the water level of an observation well 2 miles NW. of Cambridge.

Well or image	Distance, r		Chart factor	Drawdown
	(Miles)	(feet)	(K)	(feet)
Pumped well	3	15,840	903	40.1
Northwest	11½	60,700	587	26.1
East-southeast	12½	66,000	570	25.3
North	19	100,300	467	20.6
East-northeast	22½	118,800	433	19.2
Northeast	24	126,700	422	18.8
				150.1

Thus it is seen that under these assumptions, with two near boundaries, 2,000 gallons a minute continuously (2,880,000 gallons a day), or 1,051 million gallons a year, additional, could be taken for 50 years. At the end of that time the producing sand would be in the process of being dewatered, and it would be necessary to operate thereafter under changed conditions of withdrawal.

Now it is in order to calculate the maximum additional quantity of water that could be taken in the same 50-year period under more liberal assumptions, utilizing the formation constants determined in the test. These assumptions are that there are no boundaries other than the outcrop zone about 40 miles away, and that this zone is a recharge boundary capable of supplying water in direct proportion to the drawdown caused by pumping at Cambridge. This line of reasoning has already been explored for the period up to 1951 in the table on page 29. The following table sums up what would happen at present rates of pumpage for these assumptions during the next 50 years. Again, it should be pointed out that the calculations do not take into account the impermeable boundary that probably exists, though at an unknown distance, down the dip. However, it could be assumed that the aquifer down the dip comes in contact with a permeable aquifer above or below, even though the aquifer itself grades into impermeable material. Or, it could be assumed that the possible leakage from above, mentioned on page 14, cancels the effect of the down-dip boundary.

Comparison of tables on pp. 17 and 29 shows that the theoretical net drawdown to the present day on the assumptions of one recharge boundary at 40 miles would be 35.32 - 3.47 = 31.85 feet. Pumping for the next 50 years at the same rate as the average of the last few years, 1,786 gallons a minute, on the same assumptions would cause a total drawdown of 33.03 feet for the entire period, or an additional drawdown of less than a foot for the next 50 years. This indicates that a steady state would almost be reached at present rates of pumping and under such liberal assumptions of recharge.

However, as indicated before, the actual drawdown in Dor-Bd 2, 2 miles northwest of Cambridge, is 68 feet, about twice the theoretical as calculated on the basis of these assumptions as to recharge.

Theoretical effect of a recharge image well field 80 miles NW. of Cambridge, pumping at the same rate as the well field at Cambridge under present rate of pumping for the next 50 years, upon the water level in an observation well 2 miles NW of Cambridge ("400-foot" aquifer).

Pumpage increment			Time			Drawdown due to pumping at Cambridge	Recharge due to image well field	Net Drawdown
	gpm	$\frac{Q}{T}$	Period to June 30, 2001	Years	Days	(feet)	(feet)	(feet)
Q_1	228	.00507	1888	113½	41,300	5.55	- 1.29	4.26
Q_2	342	.00760	1916	75½	27,560	7.89	- 1.57	6.32
Q_3	494	.01099	1932	69½	25,370	11.32	- 2.20	9.12
Q_4	133	.00295	1935	66½	24,270	3.03	- 0.57	2.46
Q_5	589	.01305	1942	59½	21,720	13.23	- 2.36	10.87
	1,786					41.02	- 7.99	33.03

However, if these assumptions as to recharge be then accepted as the most favorable possible, on the basis of present knowledge, and using the hydrologic constants obtained from the pumping test, we can make a calculation of the maximum amount of water that could be obtained during the next 50 years. That is, we are to find the increment, Q_6, that will lower the water level in an observation well 2 miles northwest of Cambridge from its present level of 65 feet below sea level to 250 feet below sea level, under the assumption that there is only one boundary, a recharge boundary 40 miles to the northwest (or a recharge well field 80 miles to the northwest). Such a computation would set the upper limit of development under the extremely liberal assumptions discussed above. The true value would have to be somewhat - perhaps considerably - less, in view of the observed decline of 68 feet as against the theoretical decline of 31.25 feet to date; also, in view of the fact that the effect of the probable leakage from above would have been to keep the actual decline of 68 feet from being still larger.

We will also assume that the center of pumping of this new increment, Q_6, is 1 mile southeast of the present city well field, placing it 3 miles southeast of the observation well, and placing the image well field 82 miles from the pumping center (or 79 miles from the observation well). By several trials we arrive at Q_6 = 11,200 gallons a minute as a good fit, demonstrated in the following table.

Theoretical effect of a new increment of pumpage, Q_6, of 11,200 gallons a minute, from a site 1 mile SE. of present city well center, for the next 50 years, upon an observation well 2 miles NW. of Cambridge, assuming one recharge boundary 40 miles NW. of Cambridge.

	Q_6 (gpm)	$\frac{Q}{T}$	Time		Distance, r (feet)	Chart factor (K)	Drawdown (feet)
			Years	Days			
Pumped well	11,200	0.249	50	18,250	15,840	902	224.6
Recharge well	11,200	.249	50	18,250	417,100	160	- 39.9
							184.7

Thus in pumping 11,200 gallons a minute (16,130,000 gallons a day), or 5,890 million gallons a year, continuously for 50 years, the water level in the observation well would be lowered 185 feet, from 65 feet below sea level to 250 below sea level, on the assumption of recharge from one boundary 40 miles distant is proportional to the pumping at Cambridge.

Therefore, under the most favorable assumptions an approximate additional 6 billion gallons a year (16.1 million gallons a day), and under the least favorable assumptions an approximate additional 1 billion gallons a year (2.9 million gallons a day) could be taken continuously for 50 years. In neither assumption has the effect of present or future pumping from other areas been considered, and both estimates would be reduced somewhat by such consideration.

Under the assumption of a single recharge boundary at 40 miles, it was shown that the theoretical drawdown in an observation well 2 miles northwest of the center of pumping, at the rates of pumping assumed for the past $63\frac{1}{2}$ years, should have been 32 feet, whereas actually the drawdown in Dor-Bd 2 was 68 feet. Under the assumption of two impermeable boundaries, one 6 miles northwest and the other 6 miles east-southeast of Cambridge, the theoretical drawdown in the observation well 2 miles northwest of Cambridge would be 114 feet, whereas actually the drawdown in Dor-Bd 2 is 68 feet. Consequently we see that under the most favorable assumptions we err by having less drawdown, and under the least favorable assumptions by having more drawdown, than that actually observed in the only well available on which a measurement was made in the past, and another at present. Either of the discrepancies between theoretical and actual water levels can be partially explained by further thought.

It is possible, for example, that the two impermeable boundaries postulated do exist, and that the water level was kept from declining the full 114 feet because of leakage from above, and possible from below. If such leakage has occurred, there is little reason to assume that it will not continue, though whether it is now, or will continue to be, in an amount proportional to the drawdown at Cambridge is completely unknown. As noted on page 14, such leakage seems to have some basis in fact because of the fall in water level of 34 feet in an unused aquifer lying about 60 feet above the "400-foot" aquifer. The analysis of the effect of leakage is just beginning to be studied, according to the method of Jacob (1946), and no practical basis for its evaluation has yet been established.

On the other hand, the assumption that the sand is in contact with other Eocene sands, so that it obtains recharge from the outcrop, may still be true. If so, the decline of water level in Dor-Bd 2 of 68 feet, compared to the theoretical water level of 32 feet, could be due to the effect of pumping in other areas.

For example, the Patuxent Naval Air Station is now taking 150,000 gallons a day from the aquifer formed by sediments of Jackson age and the Nanjemoy formation (Bennett, 1951), and it was estimated to yield 250,000 gallons a day during the war (Bennett, 1944, p. 21). During the war, pumpage from the same aquifer for the Amphibious Training Base at Solomons was about 300,000 gallons a day, and an estimated 40,000 gallons a day was pumped for the Mine Warfare Station there (Bennett, 1944, p. 22) although neither is operative now. The Solomons-Patuxent area is about 25 air-line miles southwest of Cambridge, across Chesapeake Bay. The Trappe Frozen Foods Corp., at Trappe, 9 miles north of Cambridge, is taking about 200,000 gallons a day from the "400-foot" sand. Numerous municipalities, canneries, and other industries, which are yet to be investigated, probably take water from this aquifer. It is doubtful, however, whether all the pumping in other areas could account for all the discrepancy between 68 and 32 feet.

The distance to formation boundaries, and the influence of pumping from other wells, can sometimes be detected on a water-level graph, when water levels are plotted against the logarithm of time. If continuous water-level measurements had been accumulated in the past at Cambridge, it might be possible, through careful analysis of the records, to determine much about the influence of other pumping and of boundaries, and to make a reliable prediction of the rate of decline under additional draft in the future. In order to obtain more nearly adequate observations in the future, automatic water-stage recorders have been installed on two wells, Dor-Bd 2 and Dor-Ce 19, in the Cambridge area. It is felt that, within 2 years, sufficient records will have accumulated to permit interpretations of considerable value, though many more years would be required for complete reliability.

In view of the meagerness of our knowledge of the "400-foot" aquifer thus far, it obviously is not possible to make a reliable calculation of the safe yield of the aquifer at Cambridge. Until such a calculation can be made, it might be well to consider the range from 2 to 7 billion gallons a year (or from 1 to 6 billion gallons a year additional) as bracketing the optimum yield under the least favorable and most favorable assumptions justified on the basis of present knowledge.

ESTIMATE OF THE WORK INVOLVED IN A COMPREHENSIVE INVESTIGATION OF THE "400-FOOT" AQUIFER

The foregoing facts, figures, and speculations yield two principal conclusions: First, the "400-foot" aquifer is an important water reservoir, capable of yielding large quantities of water, if properly managed, for years to come -- at present industrial rates it has yielded more than 2 million dollars worth of water, at Cambridge; second, the study of the Cambridge aquifer is a complex problem, involving work over a large area.

The work involved in an intensive short-term study of the "400-foot" aquifer would extend over Dorchester, Talbot, and Queen Anne Counties, and over parts of Kent, Caroline, and Somerset Counties. Approximately 750 wells for which completion reports have been filed with the State would have to be located and scheduled in the field (depth, diameter, rates of yield, and current use). Graphic logs would have to be prepared in the office. Many samples of cuttings from selected wells would have to be studied in the laboratory. Graphs, charts, tables, maps, and cross sections would have to be drafted. Additional closely controlled well-field tests should be run, and the data would have to be analyzed and interpreted. Finally, the data, properly analyzed and synthesized, would have to be compiled in a report. The report would be edited, and released to open file, several years after the survey began.

It is estimated that 3 man-years would be required for the field work and preparation of the report. Probably the most effective use of personnel would involve a 2-man team working 1½ years. The total cost of the work would be $15,000 or more.

It is believed that a fair estimate of the ultimate optimum yield could be determined by such a survey. The full story, however, could be developed only by years of observation of pumping rates and water levels, analyzed periodically by an engineer experienced in ground-water hydraulics.

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Wells in the immediate vicinity of Cambridge, Md.

Measured data indicated by superscript m, all other data reported.

Owner and location	No. 1/	Depth (feet)	Diameter (inches)	Yield (gpm)	Date drilled	Altitude from map	Use	Driller	Remarks
Crystal Ice and Cold Storage Co., Washington St.	Dor-Ce 1	965½	6 to 3	125-150	1945	18	Ice	Shannahan Artesian Well Co.	This well produced water, 24 hrs. a day, throughout the year.
Do., Trenton St.	Dor-Ce 15	970½	10 to 3	200	1947	6	do	do	This well has produced water 24 hrs. a day for 5 to 6 months since 1947.
Do., Trenton St.	Dor-Ce 14	375	--	200	1890	6	do	J. J. Shannahan	Produces 22 million gallons a year. (Clark and others, 1918, p. 309, well 11).
Dorchester Water Co., Station 1, Trenton St.	Dor-Ce 7	375	12	300	1915	6	Public Supply	Shannahan Artesian Well Co.	(Clark and others, 1918, p. 309).
Do., Station 1, Trenton St.	Dor-Ce 8	375	10	300	1913	6	do	do	Do

Wells in the immediate vicinity of Cambridge, Md.--Continued

Owner and location	No.	Depth (feet)	Diameter (inches)	Yield (gpm)	Date drilled	Altitude from map	Use	Driller	Remarks
Dorchester Water Co., Station II Mill St.	Dor-Ce 10	375	10	560	1910	3	Public Supply	Shannahan Artesian Well Co.	(Clark and others, 1918, p. 309).
Do., Station III, Washington St.	Dor-Ce 4	372[m]	10 to 6	600[m]	1931	18	do	Do	Original depth 405'. Observation well during well-field test of July 23, 1951.
Do., Station III, Washington St.	Dor Ce 5	405	12	600[m]	do	18	do	Do	Combined yield with Dor-Ce 4 measured at 1160 gallons a minute July 3, 1951.
Do., Station IV, Fletcher Ave.	Dor-Ce 6	463	12 to 10	600[m]	1936	20	do	Layne-Atlantic Co.	
Do., Station V, High St.	Dor-Ce 9	460	12 to 6	700[m]	1936	25	do	Shannahan Artesian Well Co.	

Wells in the immediate vicinity of Cambridge, Md.--Contin

Owner and location	No.	Depth (feet)	Diameter (inches)	Yield (gpm)	Date drilled	Altitude from map	Use	Drilled	Remarks
Dorchester Water Co., Station VI, Dorchester Ave.	Dor-Ce 2	412	12	625[m]	1945	15	Public Supply	Virginia Well and Machinery Co.	Pumped well during test of July 23, 1951.
Do., Station VI, Dorchester Ave.	Dor-Ce 3	977	14 to 8	330	1946	15	do	Shannahan Artesian Well Co.	Produces silt first hour of operation. Clear thereafter.
Do., Station VII, Well Field	Dor-Ce 12	432	14 to 10	700	1947	15	do	Do	
Do., Station VII, Well Field	Dor-Ce 13	430	16 to 10	700	do	15	do	Do	
Eastern Shore State Hospital, 0.7 mile east of Dor-Ce 12	Dor-Ce 21	370	10	70-100	1913	8	General Plant	Do	Compressed air is used to force water out of the wells (Clark and others, 1918, p. 309).
Do	Dor-Ce 22	370	10	70-100	1921	8	do	Do	

Wells in the immediate vicinity of Cambridge, Md.--Continued

Location and owner	No.	Depth (feet)	Diameter (inches)	Yield (gpm)	Date drilled	Altitude from map	Use	Driller	Remarks
City Dairy B. G. Twilley, Boundary Ave. Between Pine and Central Sts.	Dor-Cd 1	422	$2\frac{1}{2}$	--	--	15	Industry	W. Todd and L. Jarrett	Very little water used.
Phillips Packing Co., Inc., S. E. part of Cambridge	Dor-Ce	293	6	150	1903	15	None	Shannahan Artesian Well Co.	
Do	Dor-Ce 18	293	6	150	do	15	do	Do	Static water level when drilled was 16' below land surface. In May 1951 the water level was 50' below land surface.
Phillips Oil Co., Gay and Court Lane	Dor-Ce 19	360	$2\frac{1}{2}$	--	--	5	None do	--	Observation well with automatic water-stage recorder. (Clark and others, 1918, p. 309, well 8).
D. Moore, Gay and High Sts.	Dor-Ce 20	378m	$4\frac{1}{2}$	--	1909	25	do	Shannahan Artesian Well Co.	Original depth 405'. Potential observation well. (Clark and others, 1918, p. 309, well 7).

Wells in the vicinity of Cambridge, Md.--Continued

Owner and location	No.	Depth (feet)	Diameter (inches)	Yield (gpm)	Date drilled	Altitude from map	Use	Driller	Remarks
C. Slagle, Hambrook Bar	Dor-Bd 2	380	6	150	1904	3	None	Shannahan Artesian Well Co.	Flowed 15 gpm when drilled. Observation well with automatic water-stage recorder (Clark and others, 1918, p. 309).
Cambridge Gas Co., Cherry St.	Dor-Ce 18	359	6 to 4½	--	1893	6	do	do	Static water level when drilled was 10' below land surface. Potential observation well.
N. Darrick, Henry St.	Dor-Ce 23	18^{m}	48	--	1884	14	Domestic	A. Vane	Dug well. Water used for cooking and drinking. Becomes dry periodically during summer.
E. Fairfax, Trenton St.	Dor-Ce 24	16.8^{m}	60	--	--	14	do	--	Dug well.
J. Warst, Blossom Ave.	Dor-Ce 25	20.4^{m}	48	--	1870	18	do	--	Do
O. Hubbard, Washington St.	Dor-Ce 26	11.1^{m}	28	--	--	16	do	--	Do