INVESTIGATION OF GROUNDWATER SUPPLY FOR NAVAL POWDER FACTORY NSWC INDIAN HEAD MD

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Investigation of ground water supply for Naval Powder Factory, Indian Head, Md.

by
A. G. Fiedler

With Appendix
by
C. E. Jacob

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Geological Survey
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ILLUSTRATIONS

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Introduction

This investigation of the ground-water supply that is available for possible development on the Naval Powder Factory Reservation at Indian Head, Maryland, was made by the Geological Survey in response to a request, dated January 4, 1938, from the Secretary of the Navy addressed to the Secretary of the Interior. This more intensive investigation was an outgrowth of the recommendations resulting from a preliminary study of the ground-water supply at Indian Head that was made during the summer of 1937. The results of the preliminary study are given in a report,[1/] that was transmitted to the Bureau of Ordnance, Navy Department, in October 1937.

The Naval Powder Factory reservation is situated on the east bank of the Potomac River in Charles County, Md., just north of the mouth of Mattawoman Creek. The reservation adjoins the village of Indian Head and is approximately 22 miles southwest of Washington, D. C.

Ground water is especially desirable as a source of water supply for the manufacturing operations conducted at the Naval Powder Factory because of its superior chemical quality in comparison with water from the Potomac River and Mattawoman Creek, which bound the government reservation on the west and east sides respectively. The present water supply for the manufacture of powder is obtained from eight wells situated on the government reservation in the vicinity of pumphouse No. 1. There is also a stand-by system consisting of

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1/ Fiedler, A. G., Cady, R. C., and Meinzer, O. E., The water supply available to wells on the government reservation at Indian Head, Md., Oct. 1937.

five wells situated in the vicinity of pumphouse No. 2, which is about half a mile northeast of pumphouse No. 1. The wells also furnish water for domestic use for the personnel quartered on the reservation and the people living in the adjoining village of Indian Head. (See figure 1).

The investigation was conducted under the general supervision of Oscar E. Meinzer, geologist in charge of the Division of Ground Water, Geological Survey. A. G. Fiedler was in immediate charge of the work and was assisted in the field by D. J. Cederstrom and Roy C. Meinzer. The geologic studies conducted in the intake area of the formations tapped by wells at the Naval Powder Factory and the survey of the water supply facilities at nearby government reservations in Virginia and Maryland were made by Mr. Cederstrom. He assisted also in the collection of well observation data during the pumping tests conducted on well No.11. Roy C. Meinzer, assisted at times by L. F. Burris and George O. Polley, collected the data on the pumping tests run on the wells at pumphouse No. 1. The extensive computations based on the voluminous records collected during the course of the pumping tests and the mathematical analysis of the records were made by C. E. Jacob, who devoted more than four months to this phase of the work. The report was reviewed by several members of the Division of Ground Water, of the Geological Survey, and acknowledgments are due to A. N. Sayre, D. G. Thompson, and L. K. Wenzel for constructive criticism and assistance in the interpretation of some of the base data. Especial acknowledgments are due C. V. Theis, of the Geological Survey, for devising the method of pumping analysis involving the use of an image well to determine the theoretical effect of pumping at various rates and the theoretical quantity of water that could be pumped for various periods from wells at Indian Head.

Throughout the course of the present investigation the officers and civilian personnel connected with the Naval Powder Factory extended cordial cooperation, and the necessary pumping tests of existing wells were accordingly greatly facilitated. Especial acknowledgments are due to Capt. P. B. Haines, Commander A. D. Mayer, and Lieut. Commander C. T. Tyler. Mr. C. Lancaster, Supt of the Engineering Department, was particularly helpful in arranging for the installation and operation of water-stage recorders on representative wells and in maintaining the well pumps in operation at different rates in order that essential observations on the effect of pumping could be made.

Purpose of Investigation

The purpose of the investigation was to determine more accurately than was possible during the preliminary studies of 1937, the quantity of water that could be developed from wells at Indian Head, without exhausting the supply. Specifically, the problem initially was to determine whether as much as 12,000,000 gallons of water a day could be developed from wells. The preliminary studies made in 1937 indicated that such a development would be impracticable. However, the data collected during the preliminary investigation were only general in nature. Accordingly, more extensive testing of the wells and further study of the problem were recommended in the preliminary report.

During the preliminary study in 1937 only such observations and tests were made as could be conducted without changing the operating procedure that was regularly followed at pumping plant No. 1. During the present investigation, however, a definitely planned schedule of pumping operations was conducted so that the effect of different rates of pumping could be observed and evaluated.

Geology

The geology of the region in the vicinity of Indian Head is briefly described in the preliminary report _/ as follows:

_/ Fiedler, A. G., Cady, R. C., and Meinzer, O. E., op. cit. pp. 2 & 3.

"Indian Head and the area surrounding it are underlain chiefly by alternating beds of poorly consolidated clay, silt, and sand. _/ These beds rest upon an

_/ For a detailed description of the character of the poorly consolidated beds overlying the crystalline basement rock see U. S. Geological Survey Folios 152 and 182. See also Clark, W. B., Mathews, E. B., and Berry, E. W., The Surface and Underground Water Resources of Maryland, including Delaware and the District of Columbia: Md. Geol. Survey Spec. Pub., vol. X, pt. 11, 1918.

eroded floor of crystalline rock that slopes toward the east or southeast. * * * * * * * The oldest of the formations into which these poorly consolidated materials have been classified is the Patuxent. This formation consists chiefly of buff and light-colored sands and predominately light-colored clays and sandy clays. It appears to constitute the 440 feet of material encountered between depths of about 300 feet to 740 feet in well 15, as shown in Fig. 2 (in this report) supplied by the Bureau of Ordnance. The overlying 35 feet of material, consisting largely of dark brown clay, may belong either to the Patuxent formation below, or the Patapsco formation above. Above this clay there is about 225 feet of material consisting chiefly of highly colored and variegated clay which probably belongs to the Patapsco formation. The uppermost 50 feet of material, composed chiefly of dark gray clay, and dark green sand belongs in the Aquia formation. The Patuxent and Patapsco formations are Lower Cretaceous in age; the Aquia formation is lower Eocene".

The distinction between the Patuxent formation and the Patapsco formation is not clearly drawn in some areas outside of Indian Head; hence these formations will be designated in this report as the beds comprising the Potomac group.

Figure 3 is a geologic map of parts of Maryland and Virginia, showing the area of outcrop of the formations underlying the Government reservation at Indian Head, Maryland, and the location of wells. The unconsolidated sands and clays comprising the Potomac group crop out in a strip, approximately four to six miles wide, bordering the Potomac River on the west. (See figure 3). An excellent view of the beds of the Potomac group may be seen in road cuts along U. S. Highway 1 between Fort Belvoir (formerly Camp Humphreys) and Triangle. They are seen to consist of arkosic (feldspathic) sands and clays. The beds are generally lenticular, and they thicken, thin or pinch out in relatively short distances. The sands are characteristically cross-bedded. Some of them are quite permeable, others contain more or less silt or clay. In some places the clay is so abundant that the permeability of the sand is greatly reduced.

The lack of regularity in the bedding of the Potomac group is also shown by a study of the well logs in areas where it is penetrated.

Table 1 shows the altitude of the bottom of thick beds of sand in the wells at Pumphouse No. 1 at Indian Head. These wells are located within a radius of about 300 feet of Pumphouse No. 1. It is seen that some sands maintain a nearly constant altitude in several wells while in other wells sands occur at higher or lower altitudes even within the small area included by the wells.

A similar tabulation on the wells at the Marine Base at Quantico, Va., where the wells are more widely spaced shows a greater irregularity. (See page 7).

The clay beds of the Potomac group are almost as irregular as the sands. Hence, although no individual bed of sand extends for any great distance, the ground water migrates from one sand bed to another with comparative ease.

Table 1.— **Depth of wells (in feet), and altitudes of top and bottom of wells, and of thick beds of medium or coarse sands encountered in wells (in feet above or below sea level) at Indian Head, Md. and Quantico, Va.**

	Government wells at Indian Head, Md.								
	No. 6	No. 7	No. 5	No. 8	No. 1	No. 4	No. 2	No. 9	No. 1
Depth	: 398	419	395	397	388	394	409	390	120
Altitude of surface	: +38.3	+38.9	+42.8	+36.1	+29.0	+33.8	+26.6	+32.1	+3
Altitude of bottom of well	:-360	-380	-352	-361	-359	-360	-382	-358	
Altitude of bottom of beds of sand	:		-108			-113	-89		
	-190	-194	-201	-203	-193	-206	-193	-163	-1
	-223	-226	-237	-236		-241		-210	
	-272	-266	-282	-282	-310	-290	-304		-2
	-357	-357	-353	-359	-358	-350	-363	-343	-34
									-4

Table 1 (continued)

Wells at Marine Base, at Quantico, Va.

	No. 1	No. 2	No. 3	No. 4	Test No. 1	Test No. 2
Depth in feet :	358	360	355	581	391	350
Altitude of surface :	+8	+28	+8	+8	+45	+27
Altitude of bottom of well :	-350	-332	-347	-573	-346	-323
Altitude of bottom of beds of sand:	-	-	-	-32	-28	-
	-	-45	-	-	-	-
	-	-60	-60	-	-	-
	-72	-85	-82	-94	-	-103
	-	-	-	-	-162	-
	-	-	-185	-	-178	-183
	-	-	-208	-	-	-213
	-227	-222	-230	-	-	-
	-287	-	-	-277	-	-273
		-327	-328	-	-303	
			-347	-		
				-374		

The dip of the Potomac strata is difficult to determine. Earlier investigators concluded that the dip was to the southeast at a rate of about 60 feet to the mile. Later investigations indicate that the dip is considerably less and may be not more than 30 feet to the mile. _/

_/ Mr. N. H. Darton stated to D. J. Cederstrom on November 18, 1938, that he believed 60 feet per mile to be much too high.

Immediately west of the belt of Cretaceous strata is an area of granitic rocks (which includes some areas of slate), frequently called the crystalline complex or the basement rock. The line of contact of the soft Cretaceous strata with these hard rocks is called the Fall Line, or more properly, the Fall Zone. East of the Fall Zone the surface of the basement rock slopes toward the southeast. (See figure 4a). The rock surface is irregular and its slope varies greatly from place to place. Thus at the Quantico Marine Base bedrock lies from 330 to 360 feet below sea level on either side of the railroad tracks from the aviation field to Quantico Creek. Test well 2 at Quantico, 1½ miles west of the railroad, encountered granite at 312 feet. The slope of the bedrock was calculated to be 25 feet per mile between this well and well 1, at the Marine Base. Well 4, which is nearest the Potomac River, but only about 1/4 mile from well 1, was drilled to a depth of 540 feet below sea level without encountering bedrock.

Only one well at Indian Head has been drilled to the bedrock. This is well 15, which is about 9 miles down dip from the outcrop of the basement rock. It encountered the basement rock at 740 feet below the surface. The difference in elevation between the well site and the outcrop is about 260 feet and the average slope of the bedrock is therefore about 100 feet to the mile. It is concluded from the logs of wells at Quantico that the descent is not uniform.

The surface of the basement rock, where it is exposed west of the Fall Zone (see pl. 4b), is covered in most places by a mantle of soil. The rock is here fractured and broken and water occurs in the cracks of the rock, but the fractures become less numerous with depth. The rocks contain fewer fractures beneath the cover of the Potomac group.

Along the Fall Zone both the basement rock and the Potomac group are overlain in most places by terrace deposits which are flat-lying beds of sand and gravel as much as 30 feet thick (see figure 4b). These deposits are notably permeable. However, they have been somewhat dissected by stream erosion, and are thus kept more or less drained of their ground water.

Character of water-bearing beds in intake area in relation to recharge.

The recharge of the water-bearing beds tapped by the wells at Indian Head occurs largely on the outcrop area of these beds. Some of the water that falls as rain or snow percolates into the permeable sands, migrates down the dip of the strata and becomes available to progressively deeper wells to the southeast. The highly permeable terrace deposits also absorb considerable amounts of the precipitation and, where they overlie permeable sands in the Potomac group, they transmit some of the water slowly into these sands. Some water may reach these sands by percolating downward through cracks in the basement rock and thence migrating laterally, but it is believed that the contribution from this source is small.

Some recharge of the water-bearing sands of the Potomac group may occur from the Potomac River and its tributaries where these stream channels cross the outcrop areas of the sands, providing the water level in the sands is low enough to permit recharge. It is probable that such recharge, if it exists, varies greatly from time to time. Under normal conditions of stream flow the stream bed is usually blanketed by a layer of mud or silt which, because of its relatively low permeability, hinders or perhaps prevents much movement of water through it. However, during and immediately after periods of high water, when the velocity of the streams is sufficient to scour out the channels and expose the water-bearing sands directly to the surface water, there may be considerable recharge from the streams.

During very low water stages, the water of the Potomac and its estuarine tributaries, such as Occoquan Creek, may become fairly highly mineralized as discussed on pp. 46-51. Such conditions exist only during a small part of the time, and if it were supposed that this water had free access to the sands, the proportion of mineralized water entering the sands would probably be small compared with the fresh water entering them and would probably not seriously contaminate the water-bearing sands. However, as pointed out previously, the recharge from streams during low water stages is likely to be greatly impaired by a blanket of mud or silt, and the rate during such periods would probably be much less than the average rate, or perhaps the blanket of mud and silt is so effective that there is essentially no recharge during periods when the stream water is highly mineralized.

Description of wells and pumpage at Indian Head prior to 1938.

The water supply at Indian Head is derived from a group of eight wells (Nos. 1, 2, 4-9) in the vicinity of Pumphouse No. 1 situated in location block P.31, as shown in figure 1. For convenience these wells are designated as wells of group I. They range in depth from 388 to 419 feet (see table 1). Wells 1, 5-9 are equipped with deep well turbine pumps operated by direct connected motors and the remaining wells are pumped with air lift pumps.

Detailed information regarding the wells is not available. The following description of them is quoted from the preliminary report:[1] "According to

[1] Op. cit., pp. 10-12.

incomplete data furnished by the Bureau of Ordnance, the wells were apparently drilled by the cable-tool percussion method and are 8 inches in diameter at the bottom. The records on Wells 1, 2, 4-9 indicate that screens are set at either three or four levels. Presumably perforated pipe or screens made around a perforated pipe base have been used in the upper water-bearing zones, whereas the lowest water-bearing zone tapped by each well is apparently finished with a slotted Cook well screen. The altitude of the top and bottom of the screened portions of the wells is shown in the following table (table 2 of this report) * * * ."

Table 2.

Table showing altitude below sea level of the top and bottom of the screened portions of wells at Indian Head.

Well No. 6	7	5	8	1	4	2	9
.	.	.	.	.	.	.	153-163
.	.	.	.	177-189	.	180-199	.
.	.	.	187-195	.	.	.	.
.	.	.	.	.	.	.	203-213
213-223	216-226	227-238	226-237	.	231-242	.	.
.	.	.	.	.	.	.	252-262
263-273	269-278	277-289	274-285	.	278-289	266-306	.
.	.	.	.	302-316	.	.	.
.	.	.	.	.	331-347	.	323-344
338-359	338-360	338-348	336-358	343-359	351-360	342-363	.
Total length of screen 41	41	33	52	42	47	80	51

Note: The wells are arranged in the general order of their position in relation to the dip of the beds, beginning with the well farthest up the dip and following in order with the wells down the dip.

"A study of the table indicates that the main water-bearing beds that are screened are rather persistent in Wells 6, 7, 5, 8 and 4. In Well 1 only the lowest zone appears to be at a depth consistent with the corresponding zones in five other wells and the uppermost zone that is screened appears consistent with the uppermost zone in Well 2. The zones that are screened in Well 9 do not appear at depths that are at all comparable with those in the other wells, except for the lowest zone which is more or less comparable to the next to the lowest zone in Well 4."

A stand-by well system consisting of five wells (Nos. 10-14) is connected to a central pumphouse designated as Pumphouse No. 2 (see fig. 1). These wells are situated in location block S35, about half a mile northeast of Pumphouse No. 1. Four of these wells are in serviceable condition for pumping by air but well 14 cannot be pumped because the pipe line connecting it to the pumphouse has been partly destroyed. No detailed information regarding the construction of wells 10-14 is available.

According to tests [1] made by the Bureau of Ordnance in 1933, summary of

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[1] Op. cit. p. 13.

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which is given in table 3, the respective wells ranged in yield from 86 to 304 gallons a minute under drawdowns of 13 to 71 feet. The exact conditions under which these tests were made are not known but because of the wide variation in drawdown and yield, it appears likely that the yield of some of the wells was affected by the pumping of other wells in the same group.

The wells in the vicinity of Pumphouse No. 1 are relatively close to one another and the static water level for all the wells in this group should be essentially the same. The measured static water level during the 1933 tests, however, ranged from 70 to 102 feet below sea level for the wells in the vicinity of Pumphouse No. 1. A similar situation existed at the wells in the vicinity of Pumphouse No. 2, where the measured static water level ranged from 35 to 54 feet below sea level for the respective wells.

Records of pumping for the early years of the operation of the factory are not available, but the pumpage in different periods has been estimated, partly on the basis of the capacity of the wells installed in each period. During the period 1899 to 1910, inclusive, the pumpage probably averaged between 200,000 and 300,000 gallons a day. In 1910 two additional wells (Nos. 4 and 5) were installed, each of which had an estimated capacity of about 200,000 gallons a day.

Table 3. -- Summary of pumping tests conducted in 1933 of wells at the Naval Powder Factory, Indian Head, Maryland.

Well No.	Static water level: below surface (feet)	Static water level: below sea level (feet)	Pumping level: below surface (feet)	Pumping level: below sea level (feet)	Drawdown (feet)	Yield G.P.M.	Depth of air line (feet)	Specific Capacity 1/	Year drilled
1	102	73	173	144	71	150	305	2.1	1899
2	97	70	129	102	32	134	319	4.2	1902
4	118	84	167	133	49	143	287.5	2.9	1910
5	116	73	155	112	39	124	370.1	3.2	1910
6	130	92	199	160	69	248	361.9	3.6	1915
7	134	95	196	157	62	154	375.5	2.5	1915
8	127	91	173	137	46	212	335.6	4.6	1915
9	134	102	150	118	16	126	363.8	7.9	1915
10	68	54	81	67	13	86	337.4	6.6	1918
11	68	51	81	64	13	132		10.2	1918
12	75	57	127	109	52	242		4.7	191[illegible]
13	70	35	132	97	62	304		4.9	1918

1/ Yield, in gallons a minute, for each foot of drawdown.

During the period 1911 to 1915, inclusive, the pumpage probably averaged between 400,000 and 500,000 gallons a day. In 1915 four additional wells (Nos. 6, 7, 8, 9) were drilled in the vicinity of Pumphouse No. 1. During the period 1916 to 1920, inclusive, the pumpage probably increased materially, especially after the completion of the additions to the powder factory in 1918. The pumpage during this period probably averaged between 800,000 and 900,000 gallons a day. Since 1921 detailed records of pumpage have been kept. During the period 1921 to 1938 the pumpage has averaged between 500,000 and 600,000 gallons a day.

The graph in figure 5 shows the average daily pumpage by months and years for the period January 1921 to November 1938. During this period the highest pumpage occurred in 1921, when it averaged 1,110,000 gallons a day, and the second highest occurred in 1928, when it averaged 986,000 gallons a day. The highest monthly pumpage occurred in July 1921, in which month the average was 1,298,000 gallons a day. Pumpage exceeding a daily average of more than one million gallons also occurred in 8 months in 1928, 1 month in 1929 and 2 months in 1930. During the period 1921 to 1938, the lowest pumpage occurred in 1933, during which year the average was only 431,000 gallons a day. The lowest monthly pumpage was in February 1933, when the average was only 370,000 gallons a day.

Wells and pumpage at nearby Government establishments.

A survey was made in the summer of 1938 of the wells in the general area in which Indian Head is located, especially to determine whether these wells are affected by the pumping at Indian Head or whether the pumping from them affects the water supply at Indian Head. Nearly all wells in the general area were visited from which considerable quantities of water are pumped. Nearly all these wells are situated on Government reservations.

Fort Washington, Md.--The water supply for the Government reservation at Fort Washington is derived from five wells that are situated near the bank of the Potomac River. Three of these wells are 6 inches in diameter and 260 feet deep, one is 8 inches in diameter and 263 feet deep, and one is 8 inches in diameter and 280 feet deep. In the lowest well of the group the static water level on July 6, 1938 was 21 feet below the surface, or about 10 feet below sea level. The 280-foot well, which was constructed in 1930, is reported to have yielded 137 gallons a minute with a drawdown of 78 feet. The pumpage from wells is reported to have averaged about 117,000 gallons a day in 1936, and about 120,000 gallons a day in 1938.

Fort Hunt, Va.--The C. C. C. camp at Fort Hunt derives its water supply from an 8-inch well which is reported to be 290 feet deep. The well yields about 34 gallons a minute when pumped. The pumpage averages about 20,000 gallons a day, the minimum being about 15,000 gallons and the maximum about 45,000 gallons.

Mt. Vernon, Va.--There are three wells at Mt. Vernon. One well is at the lunch room, near the entrance to the grounds on which the home of George Washington is situated. It is reported to yield 60 gallons a minute, but to be used for only a small part of its capacity.

The second well is at the fire house, at an altitude of about 55 feet above sea level. The water level in this well is about 63 feet below the top of the casing. This well is now used only as an auxiliary supply.

The main supply at Mt. Vernon is obtained from the third well, which is situated on the bank of the Potomac River and is 525 feet deep. Originally this well flowed at a small rate, but pumping during recent years has drawn down the static water level to about 20 feet below sea level. According to the engineer in charge, the well is pumped at an average rate of about 10,000 gallons a day.

Fort Belvoir, Va.--At Fort Belvoir (formerly Fort Humphreys) surface water is used almost exclusively. A gravel-packed well, 279 feet deep, is located at Accotink, near the water-treatment plant, at an altitude of 24 feet above sea level. This well is available as an emergency supply. Its static level is 8 feet below the surface, or about 16 feet above sea level. According to the engineer in charge, the well yielded 250 gallons a minute during 10 days of continuous pumping, with a drawdown of 62 feet. Most of its supply appears to be derived from the bouldery material lying on the bedrock surface.

Quantico, Va.--Two wells on the Marine Corps Reservation at Quantico are described in a report by N. H. Darton [1] that was published in 1896. One of these wells was 210 feet deep and overflowed at an altitude of several feet above sea level. The other well was 350 feet deep and yielded 4 to 5 gallons a minute by artesian flow. Additional wells have been drilled at different times on the reservation, but little information is available regarding them. Four wells of a group of six drilled in 1917, were 160, 184, 225, and 587 feet in depth, respectively. Five of these six wells, together with those drilled prior to 1917, have been abandoned.

In 1930 a number of test wells were drilled on the reservation, and subsequently four gravel-packed wells were constructed. These four wells are 8 inches in diameter at the bottom and now supply the water required on the reservation. They are finished with two or more screens each.

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[1] Darton, N. H., Artesian well prospects in the Atlantic Coastal Plain region, Geol. Survey, Bull. 138, pp. 151, 166, 1896.

The following table gives pertinent information about the wells.

Wells at Marine Corps Reservation, Quantico, Va.

Well	Depth (feet)	Yield March 1933 (g. p. m.)	Yield[1] May 1933 (g. p. m.)	Yield[2] Oct. 1935 (g. p. m.)
No. 1	358	93	110	120
No. 2	360	44	59	37
3	355	148	162	149
4	581	308	367	319

1/ Average discharge on last day of 3-day test.

2/ Average discharge during 18-hour test.

The static water level of the wells at the Marine Base is approximately 0.5 foot to one foot below mean sea level. The static water level in three of the wells was measured several times a day during the period June 6 - July 2, 1938 and these measurements are shown in graphic form in Figure 6.

Detailed information on the quantity of water pumped from the wells at Quantico is not available, but for the last six months of 1932 the average daily pumpage was about 330,000 gallons. Beginning about 1935 most of the water used by the reservation was obtained from Chopawamsic Creek. In that year an average of about 770,000 gallons a day was obtained from this creek, whereas the wells supplied only about 110,000 gallons a day. In 1936 and 1937 about 150,000 gallons a day was obtained from wells.

Dalgren, Va.--The water supply for the Naval Proving Grounds at Dalgren is obtained from three wells. Well 1, drilled in 1919, is 6 inches in diameter and 735 feet deep, and yields about 90 gallons a minute when pumped with a deep-well turbine pump. Well 2, drilled in 1929, is 10 inches in diameter and 750 feet deep, and is reported to yield about 75 gallons a minute when pumped. The flow of well 1 decreased gradually following the installation of well 2, and on May 23, 1938, when well 2 was idle, the water level in well 1 was 1.5 feet below the floor of the pumphouse, which is at an altitude of approximately 15 feet above sea level. Well 3, belonging to the Government, is situated on a farm near the main reservation. It is pumped by a household water system and the water is used only for domestic purposes.

Records of pumpage at Dalgren have not been obtained in recent years, but on the basis of records for the period 1923 to 1929, it is estimated that the average daily pumpage is somewhat more than 100,000 gallons.

Summary.--The average pumpage from all the wells that have been described on the Government reservations except those at Indian Head is estimated to be between 400,000 and 500,000 gallons a day. This pumpage is widely distributed and is not near enough to the wells at Indian Head to cause direct interference with them. None of the observations of water levels in wells at Indian Head made during this investigation indicate that the yield of the Indian Head wells was adversely affected by pumping at the other Government reservations in this area. It is believed that as long as the rate of pumping at these reservations is not increased greatly above the present rate, no problem will be created that will need to be considered in connection with the development of water from wells at Indian Head.

Capacity of wells at Indian Head in 1938.

Because of the constant demand for water, it was not practicable to shut down all the wells and make individual tests of each well during the present investigation. However, limited information on the present capacity of individual wells was secured during the course of the pumping tests that were made for the purpose of obtaining basic information on the rate that the water-bearing formations tapped by the wells at Indian Head would yield water.

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The static water level of the wells at the Marine Base is approximately 0.5 foot to one foot below mean sea level. The static water level in three of the wells was measured several times a day during the period June 6 - July 2, 1938 and these measurements are shown in graphic form in Figure 6.

Detailed information on the quantity of water pumped from the wells at Quantico is not available, but for the last six months of 1932 the average daily pumpage was about 330,000 gallons. Beginning about 1935 most of the water used by the reservation was obtained from Chopawamsic Creek. In that year an average of about 770,000 gallons a day was obtained from this creek, whereas the wells supplied only about 110,000 gallons a day. In 1936 and 1937 about 150,000 gallons a day was obtained from wells.

Dalgren, Va.--The water supply for the Naval Proving Grounds at Dalgren is obtained from three wells. Well 1, drilled in 1919, is 6 inches in diameter and 735 feet deep, and yields about 90 gallons a minute when pumped with a deep-well turbine pump. Well 2, drilled in 1929, is 10 inches in diameter and 750 feet deep, and is reported to yield about 75 gallons a minute when pumped. The flow of well 1 decreased gradually following the installation of well 2, and

The wells situated in the vicinity of pumphouse No. 1 (Nos. 1, 2, 5-9), discharge into one end of a long sump adjoining the pumphouse. This sump is subdivided by walls into several compartments which act as sedimentation chambers. The water flows from one chamber to the next through a rectangular opening near the top of the dividing wall and enters at one end of a chamber and flows out at the far end. After the water flows through the first sump, it is discharged into a second sump from which it is pumped into the distribution system. In order to measure the quantity of water pumped during the tests and to check the quantity recorded by the flow meter installed in the main distribution line, a rectangular weir was installed between the two sumps. The head of water flowing over the weir was measured by a water stage recorder installed in the first sump.

The weir was calibrated by measuring volumetrically the quantity of water discharged during a definite period into the second sump, while the head of the water flowing over the weir was maintained at a constant level. The capacity of the second sump was computed to be equal to 95.16 gallons for each one-hundredth of a foot of depth. The calibration tests were begun by pumping one well until the head of water flowing over the weir remained constant. The rise in the water level in the second sump during a definite period was then measured. The rate of discharge corresponding to the head of water over the weir was computed from the measurements of the rise of the water level in the second sump. This procedure was repeated for a number of different rates of pumpage. Pertinent information on the calibration tests is given in table 4.

The data given above were plotted as shown in figure 7, anddefine a mean curve from which the rate of discharge corresponding to different heads of the water flowing over the weir can be readily determined. The rating table (table 5) derived from the mean curve is given on page 21.

Table 4. Measurements of discharge for calibration of weir at Pumphouse 1.

Date 1938	Wells pumped	Time starting of run	Time end of run	Gage height start	Gage height end	Average gage height	Rise of water level in Sump 2 (feet)	Quantity discharged (gals.)	Gall. pe minu
		p.m.	p.m.						
June 6	1	2.14	2.34	2.215	2.215	2.215	.260	2,474	123.
	1,6	2.56	3.08	2.278	2.278	2.278	.360	3,426	285.
	1,6,8	3.38	3.53	2.333	2.334	2.334	.740	7,042	469.
	1,5,6,8,9	4.47	4.51	2.426	2.426	2.426	.335	3,188	797.
	1,5-9	5.05	5.11	2.460	2.460	2.460	.595	5,662	944.
Aug. 2	1,2,6-9	1.14	2.24	2.42	2.42	2.42	0.84	7,993	799.
	2,6-9	1.46	1.54	2.395	2.395	2.395	.59	5,614	701.
	2,6,7	1.57	2.07	2.28	2.28	2.28	.325	3,093	309.
	2,6	2.17	2.27	2.24	2.24	2.24	.175	1,665	166.
	2,6,8	2.38	2.48	2.302	2.302	2.302	.405	3,854	385.
	2,6,8,9	3.00	3.10	2.358	2.358	2.358	.600	5,710	571.

Table 5. Rating table for weir at Pumphouse 1.

Gage height (feet)	Gallons per minute	Gage height (feet)	Gallons per minute
2.15	0.0	2.33	460
2.16	15	2.34	494
2.17	31	2.35	529
2.18	48	2.36	564
2.19	66	2.37	600
2.20	86	2.38	637
2.21	108	2.39	674
2.22	131	2.40	712
2.23	155	2.41	750
2.24	181	2.42	788
2.25	208	2.43	826
2.26	236	2.44	864
2.27	266	2.45	902
2.28	297	2.46	940
2.29	328	2.47	979
2.30	360	2.48	1018
[illegible]	[illegible]	2.49	1058
2.31	393	2.50	1098
2.32	426		

There is marked interference between wells of group I and accordingly the calibration tests do not furnish an accurate measure of the capacity of each well when pumped individually for a considerable period. However, the tests do give information by which the relative capacities of the individual wells may be judged. The capacities given in the following table are approximate. They represent the amount that the total discharge of the pumped wells increased when the particular well was pumped.

Capacity of wells of group I
(Based on tests made June 6 and Aug. 2, 1938)

Well No.	Discharge (g.p.m.)	Well No.	Discharge (g.p.m.)
1	124	7	145
2	38	8	184
5	132	9	186
6	162		

The capacities determined from the calibration tests for the seven wells at pumphouse No. 1 were generally less than those determined during the 1933 tests (see table 3).

The lower discharge in 1938 as compared with that in 1933 can, in part, be accounted for by the fact that, as shown in figure 5, the pumpage for several months in 1933 preceding the tests was considerably less than that which preceded the tests in 1938. Accordingly, the regional head in the water-bearing formations was probably somewhat higher than that in 1938. Furthermore, the capacities determined during the 1938 tests, described previously, were obtained while more than one well was being pumped and since interference between wells is relatively great, the combined capacity of several wells pumping at the same time is markedly less than the combined capacity of the same wells when pumped individually.

Only well 11 in group II was pumped during this investigation, and data are not available as to the present capacity of the other wells of this group. Well 11 was pumped by air from 1:23 p.m. July 11 to 3:21 p.m. July 15, during which time no change was made in the operation of wells 1, 5, 7, 9 of group I which were being pumped at the average rate of 700 gallons a minute. The discharge of well 11 was determined by measuring for definite periods the rise in the water level in the sump of pumphouse No. 2, in which the water from well 11 was collected. Because the capacity of the sump was insufficient to hold all the water pumped during the pumping test, it was necessary to drain the sump at intervals, during which periods no change was made in the operation of well 11. Continuous measurements of the discharge could not be made, therefore, because of the interruptions due to draining the sump. However, the rate of discharge as computed from the rise of the water level in the sump during the period 1:23 p.m. July 11 to 8:40 a.m. July 15 remained relatively uniform and averaged 64.8 gallons a minute. During a period when the sump was being drained the discharge of the well increased noticeably and from about 8:40 a.m. to 3:21 p.m. July 15 it averaged 100.6 gallons a minute. The reason for this marked increase in yield is not definitely known, but it is likely to have been due to either a greater amount of air supplied the pump, or to the opening up of the intake facilities of the well with continued pumping. It is concluded that the present capacity of well 11 is about 100 gallons a minute.

Since it was not feasible to measure accurately the drawdown in the respective wells during pumping, no logical basis of comparison between the present discharge and the discharge of the wells in 1933 exists. Furthermore, the setting of the pumps in the wells in 1938 differed from that in 1933. Because of the marked interference between wells and the effect on the regional static water level caused by pumping immediately prior to any controlled pumping test, the only satisfactory basis for comparing the yield of the respective wells at different periods would be to repeat at intervals a pumping test during which pumping operations were maintained the same as during a previous test. Such a comparison can be made in the future by repeating the extended tests made in June and July 1938, which will subsequently be discussed in detail in this report and for which accurate data are now available.

Original and present head of the ground water.

According to Darton [1] one of the first wells constructed on the Indian

[1] Darton, N. H., Artesian well prospects in the Atlantic Coastal Plain Region: U. S. Geological Survey Bulletin 138, pp. 134-135, 1896.

Head reservation was drilled some time prior to 1896 and was 463 feet deep. This well was situated near the Potomac River at an altitude of about 100 feet above low-water, and the water in the well rose to about 10 feet above low-tide level. It yielded 11.6 gallons of water per minute when pumped. Information in regard to the head and yield of wells Nos. 1 to 3, is given in the report of the Maryland Geological Survey. [2] According to this report, the head of the water

[2] Clark, W. B., Mathews, E. B., and Berry, W. E., The surface and underground water resources of Maryland, including Delaware and the District of Columbia: Md. Geol. Survey Spec. Pub., Vol. X., pt. II, p. 397, 1918.

in Well No. 1 was 3 feet above sea level, it flowed 20 gallons per minute, and the well yielded 104 gallons per minute when pumped. The head in Wells Nos. 2 and 3 is given as being above sea level and their yield as 100 gallons and 83 gallons a minute respectively when pumped. The date of these measurements of head and yield is not definitely known. They were probably made a considerable time before 1918, when the report was published.

Because of the continued demand for water for use on the Government reservation and the adjoining village of Indian Head, the pumping of wells of group I could not be interrupted during the present investigation for a sufficiently long enough period for the water level in the wells to recover to essentially its static position. The static water level shown in table 3, page 13, based on the 1933 tests of wells of group I, unquestionably is not a true static level. The static water levels in these wells should be nearly the same, whereas it varies from a level of 70 feet below sea level for well 2, to 102 feet below sea level for well 9. The respective levels were therefore influenced by earlier pumping from the wells.

Prior to any extensive pumping at Indian Head the wells of group II, except well 14 which is situated on higher ground, either flowed or had static water levels that were very close to the surface. The approximate agreement of the static water levels recorded in the 1933 tests for wells 10, 11, 12 (see table 3, page 13) creates a presumption that these wells show the approximate static level in 1933 in the vicinity of pumphouse No. 2. The higher level of well 13 was due to some unexplained cause.

In 1938 the water level of well 10 on June 8 (see table 7, page 29) was 51.51 feet below sea level and on June 30 at the end of heavy pumping of wells of group I, it was 72.50 feet below sea level. Thus, the water level recorded for wells of group II during this investigation represent conditions unaffected by pumping in their immediate vicinity but affected by pumping of wells of group I.

Pumping tests at Indian Head

In order to obtain basic information from which to determine the rate that water is transmitted through the formation and the quantity of water that could be recovered from storage in the water-bearing materials, carefully controlled pumping tests were conducted on wells of group I and on well 11 (see figure 1). Prior to the beginning of the tests, wells of group I had been pumped at varying rates according to the demand (see figure 8). Wells of group II had not been operated for several years except for brief periods at infrequent intervals to check the pumping equipment. The test of wells of group I was begun at 8:00 a.m. June 8, 1938 and wells 1, 6, 8, and 9 were pumped continuously for twelve days. The combined average pumping rate for the period was 644 gallons a minute. At 8:00 a.m., on June 20, pumping was started with wells 2, 5, and 7. The yield was thus increased, and averaged 827 gallons a minute for the next 10 days. At 11:00 a.m. on June 30 pumping of wells 2 and 6 was discontinued. The remaining five wells (1, 5, 7-9) were pumped at a combined average rate of 697 gallons a minute until 5:00 p.m. July 19, when the test was discontinued. Thus the pumping test on these wells may be divided into three periods as follows:

Period	Beginning	End	Wells pumped	Combined average yield
First	8 a.m. June 8	8 a.m. June 20	1,6,8,9	644 g.p.m.
Second	8 a.m. June 20	11 a.m. June 30	1,2, 5-9	827 g.p.m.
Third	11 a.m. June 30	5 a.m. July 19	1,5, 7-9	697 g.p.m.

During the latter part of the third period of the test on wells of group I, a pumping test was run on well 11 of group II. Well 11 was pumped at an average rate of 67.1 gallons a minute beginning 1:23 p.m. July 11 and ending 3:21 p.m. July 15.

The pumpage from wells of group I was computed by determining with a planimeter the mean daily head of the water over the discharge weir installed at pumphouse No. 1 and applying the head to the rating table (see table 5). For convenience the pumpage was computed by days beginning at 8:00 a.m. rather than at midnight. Table 6 shows the average daily discharge of the wells.

No change was made in the respective pumps during the period that each was in operation. During the first period of the test (see p. 28) the average daily rate remained relatively constant and averaged 644 gallons a minute. The rate of discharge at any time, however, fluctuated slightly as shown in table 7, which gives the rate of discharge at 8:00 a.m. for each day. During the second period of the test (see p.) when 7 wells were pumped continuously,

Table 6. Discharge of wells of Group I

during pumping tests.

(For days beginning at 8:00 a.m.)

Date 1938	Discharge (g.p.m.)	Date 1938	Discharge (g.p.m.)
June 8	635	June 29	753 a/
9	650	30	756
10	642	July 1	675
11	642	2	686
12	642	3	686
13	642	4	704
14	642	5	713
15	646	6	717
16	656	7	720
17	650	8	704
18	642	9	713
19	638	10	708
20	907	11	728
21	867	12	713
22	870	13	696
23	845	14	675
24	841	15	679
25	832	16	690
26	806	17	686
27	780	18	682
28	791	19	671

Wells 1,6,8,9 pumped 8 a.m. June 8 to 8 a.m. June 20.
Wells 1,2,5-9 pumped 8 a.m. June 20 to 11 a.m. June 30.
Wells 1,5,7-9 pumped 11 a.m. June 30 to 5 a.m. July 19.
a/ Well 6 not operating 3 hr. 35 min. during period 8:20 a.m. - 4:45 p.m. June 29.

Table 7. Discharge at different times of wells of group I and water level for corresponding times in wells 4 and 10.

Date 1938	Time	Wells pumped	Discharge G.P.M.	Water level, feet below sea level Well 4	Well 10
June 8	8:00 a.m.	1,6,8,9	637	97.34	51.51
9	do	do	637	105.34	53.81
10	do	do	637	107.34	55.51
11	do	do	641	108.62	56.61
12	do	do	674	109.47	57.56
13	do	do	637	110.22	58.51
14	do	do	641	110.84	- --
15	do	do	637	111.17	59.41
16	do	do	633	111.44	59.89
17	do	do	656	111.76	60.22
18	do	do	630	111.86	60.71
19	do	do	637	112.54	61.11
20	do	do	630	112.69	61.33
20	10:00a.m.	1,2,5-9	921	129.77	61.16
21	8:00a.m.	do	835	141.86	63.26
22	do	do	833	145.16	65.28
23	do	do	845	146.94	67.06
24	do	do	826	148.10	68.48
25	do	do	826	148.89	69.41
26	do	do	826	149.44	70.81
27	do	do	788	149.88	70.81
28	do	do	781	150.54	71.31

Date 1938	Time	Wells pumped	Discharge G.P.M.	Water level, feet below sea level[a] Well 4	Well 10
June 29	8:00a.m.	1,2,5-9	788	150.82	71.79
30	do	do	750[b]	145.09	72.06
30	1:00p.m.	1,5,7-9	637	143.08	72.50
July 1	8:00a.m.	do	655	137.74	71.59
2	do	do	674	136.59	70.86
3	do	do	681	136.19	70.46
4	do	do	708	136.09	70.26
5	do	do	708	136.01	70.34
6	do	do	712	135.94	70.27
7	do	do	705	135.87	70.11
8	do	do	712	135.84	69.96
9	do	do	712	135.79	69.88
10	do	do	712	135.77	70.08
11	do	do	708	135.88	70.06
12	do	do	719	136.07	80.61
13	do	do	712	136.82	83.25
14	do	do	674	137.16	84.33
15	do	do	667	137.63	85.51
16	do	do	674	137.98	75.66
17	do	do	693	137.44	73.01
18	do	do	681	136.90	71.56
19	5:00a.m.	do	674	136.84	71.73

Wells 1,6,8,9 pumped 8:00 a.m. June 8 to 8:00 a.m. June 20.
Wells 1,2,5-9 pumped 8:00 a.m. June 20 to 11:00 a.m. June 30.
Wells 1,5,7-9 pumped 11:00 a.m. June 30 to 5:00 a.m. July 19.
Well 11 pumped 1:23 p.m. July 11 to 3:21 p.m. July 15.

a/ Water levels not corrected for tide, barometric effect and trend due to continuous pumping.

b/ Well 6 out of operation total of 3 hr. 35 min. during period 8:20 a.m. - 4:45 p.m. June 29.

the discharge declined constantly. The rate for the first 24-hour period beginning 8:00 a.m. June 20 when 7 wells were pumped was 907 gallons a minute. After ten days of pumping, however, the discharge had declined to an average of 753 gallons a minute.

As explained previously (see p. 23), a pumping test on well 11, of group II, was run from 1:23 p.m., July 11, to 3:21 p.m., July 15, during which time wells of group I were pumped constantly at an average rate of 700 gallons a minute. The average rate of pumping for well 11 for the period indicated above was 67.1 gallons a minute.

Water-level measurements

At frequent intervals during the pumping tests tape measurements were made of the water levels in wells 11, 12, and 13. Water-stage recorders were maintained in continuous operation on wells 4, 10, and 14. All water levels taken from the recorder graphs and all tape measurements of depth to water in wells were converted to altitude in feet above or below mean sea level. All measurements of depth to water in wells were made from measuring points on the top of the casing of the respective wells. The altitude of the measuring points given in the following table was determined by spirit leveling.

Altitude, in feet above sea level, of measuring points of wells.

Well	
4	34.66
10	13.89
11	16.51
12	18.67
13	33.23
14	39.24

Correction of water levels for tidal and barometric fluctuations.

The water levels in the wells at Indian Head fluctuate in response to the tide in the Potomac River and Matawoman Creek nearby and also in response to changes in barometric pressure. To obtain information on the tidal and barometric changes a water-stage recorder was operated as a recording tide gage on Mattawoman Creek near well 10 beginning June 10 and a microbarograph was operated at Indian Head beginning June 9. Hourly measurements of the level of the tide were also obtained from a float-operated tide gage situated at the Indian Head wharf on the Potomac River.

Because of the large area covered by tidal water in the vicinity of Indian Head and the relative proximity of the wells thereto, there is very little lag between the tide and the fluctuations produced in the wells. It is assumed that the rise or decline in water level in the observation wells caused by the tide is proportional to the rise or fall of the tide which produces the fluctuation, the ratio between the two being termed the "tidal efficiency" of the particular well. Tidal efficiency of each well was determined by comparing the difference between low tide and the preceding or following high tide with the corresponding difference between low and high water levels in the well, a factor being applied to the latter to correct for the general trend of the water level caused by changes in the rate of pumping from wells of group I. By averaging a number of such determinations, the tidal efficiencies shown in the following table were obtained.

Tidal efficiency of Indian Head wells

Well	
10	0.27
11	0.27
12	0.26
13	0.18
14	0.21

These values shown above are fairly reasonable and are consistent in that wells nearer tidal water have in general higher tidal efficiencies.

The observed water levels were corrected for the effect of the tide according to the difference between the observed tide at any time and the mean tide. For example, if at a certain time the tide was 1.00 feet above the mean, the water level observed at that time in well 10 was presumably 0.27 foot above the "corrected" level. The mean tide over the period of the pumping tests was determined by planimeter.

A procedure similar to that followed in correcting for tidal effect was followed in applying further corrections for the effect of fluctuations in barometric pressure. A value of 0.70 was assumed for the "barometric efficiency" for all the wells. This figure was arrived at by consideration of the tidal efficiencies of the various wells and their respective distances from tidal water. The indications are that if the aquifer in question were entirely overlain by tidal water, a well penetrating that aquifer would have a tidal efficiency of possibly 0.30.

Theoretically the sum of this limiting value of tidal efficiency and the value of barometric efficiency is unity. The corrections for tidal and barometric effects were made graphically. Figure 8 shows the tidal and barometric fluctuations, water level fluctuations in well 10, and pumpage at Indian Head for the period May 1-June 7, 1938. The water level fluctuations in well 10 were obtained by means of a water stage recorder. The graph shows a more or less regular weekly cycle of fluctuation due to the closing of the powder factory at the end of each week and the resultant curtailment in pumpage at such times.

Figure 9 shows the tidal and barometric fluctuations, the water level fluctuations in wells 10-14, and pumpage at Indian Head for the period June 8-July 10, 1938. The corrections for tidal and barometric fluctuations for the wells are also shown, together with the mean corrected water level curves for each well. The mean corrected water level curves are also shown in figure 10.

The same procedure that was followed in correcting the water level curves during the controlled test of wells of group I was used in correcting the water levels during the period July 11-19 when well 11 was pumped to determine the effect of pumping it upon the water level in the other wells. Figure 11 shows the corrected drawdown, and recovery curves for wells of group II ~~shows the corrected drawdown, and recovery curves for wells of group II~~ for the period July 11-19, during which well 11 was pumped.

<u>Effect of pumping on water levels in Indian Head wells</u>

It has been pointed out previously that the wells of group I interfere greatly with one another. This interference is shown by the effect on the water level of well 4 when other wells of the group are being operated. Table 8 shows the water level, in feet below sea level, in well 4 for the period of the pumping tests run in the summer of 1938.

Whereas the water level in well 4 at 6:00 a.m. June 8 was 93.84 feet below sea level, at the end of 13 days of pumping of wells 1, 6, 8, and 9 at an average rate of 644 gallons a minute, it had declined to 112.67 feet below sea level. The pumpage at group I was increased at 8:00 a.m. June 20 by starting wells 2, 5, and 7. The effect on the water level of well 4 was immediate and by 12:00 noon June 20 the water level had declined to 131.57 feet below sea level.

The average rate of pumpage from wells of group I from 8:00 a.m. June 20 to 11:00 a.m. June 30 was 753 gallons a minute. Some difficulty was experienced on June 29 with the operation of well 6 because of the heating of the motor and this well was out of operation a total of 3 hours and 35 minutes, at intervals, during the period 8:20 a.m. - 4:45 p.m. June 29. The effect of this is shown in the respective water levels shown in the table for June 29. The lowest level occurred, therefore, at about 6:00 a.m. June 29 and was 150.82 feet below sea level.

Table 8. Altitude, in feet below sea level, of water level in well 4 at different times for period June 8 - July 19, 1938.[1/]

Date 1938	6:00 a.m.	12:00 noon	6:00 p.m.	12:00 midnight	Date 1938	6:00 a.m.	12:00 noon	6:00 p.m.	12:00 midnight
June 8	93.84	100.44	103.04	104.34	June 29	150.82	148.94	148.42	148.42
9	105.04	105.79	106.20	106.85	30	148.26	144.69	140.06	138.76
10	107.24	107.69	107.86	108.32	July 1	138.09	137.72	137.39	136.85
11	108.46	108.89	108.99	109.31	2	136.75	136.44	136.50	136.19
12	109.42	109.72	109.76	110.08	3	136.34	136.16	136.24	136.04
13	110.21	110.43	110.54	110.76	4	136.04	135.89	136.04	135.94
14	110.34	110.34	110.91	111.04	5	135.94	135.92	135.88	135.82
15	111.14	111.24	111.34	111.44	6	135.84	135.74	135.85	135.82
16	111.75	111.53	111.56	111.64	7	135.82	135.94	135.94	135.83
17	111.75	111.79	111.97	112.04	8	135.79	136.02	135.83	135.84
18	111.72	112.04	112.34	112.34	9	135.75	135.86	135.82	135.94
19	112.49	112.48	112.66	112.55	10	135.77	135.95	135.86	136.02
20	112.67	131.57	137.34	139.66	11	135.89	135.97	135.91	136.02
21	141.46	142.22	143.24	144.16	12	136.04	136.45	136.52	136.73
22	144.94	145.44	145.92	146.39	13	136.72	136.99	137.06	137.16
23	146.84	147.04	147.42	147.80	14	137.19	137.35	137.42	137.53
24	148.06	148.00	148.19	148.53	15	137.64	137.84	137.87	137.99
25	148.73	149.06	149.09	149.34	16	137.94	137.89	137.82	137.66
26	149.39	149.69	149.66	149.92	17	137.49	137.44	137.50	137.24
27	149.75	150.12	150.06	150.48	18	136.90	136.91	136.86	136.82
28	150.45	150.84	150.74	150.82	19	136.85	136.65	136.44	133.29

1/ Water level obtained from recorder graph.

At 11:00 a.m. June 30 wells 2 and 6 were shut down and the water level in well 4 rose promptly in response to the reduction in pumpage to an average rate of 700 gallons a minute. The rise in water level continued until 1:23 p.m. July 11, when well 11, of group II, was started. The continued recovery of the water level in well 4 during July 10 and the morning of July 11 is not apparent in the values given in the table, however, as these values are uncorrected for tidal and barometric effect.

Well 11 is 2,050 feet distant from well 4, and even though well 11 was pumped at the relatively low average rate of 67.1 gallons a minute for the period 1:23 p.m. July 11 to 3:21 p.m. July 15, the effect upon the water level in well 4 is evident from a study of the values given in table 8.

The effect upon the water level in well 4 due to pumpage from the respective wells is shown graphically in figure 12.

The extent of interference between wells at Indian Head is not confined to wells that are close to the pumped well or wells. The effect on more distant wells is clearly shown in the table 7, pp. 29-30, which gives the average daily discharge of wells of group I and the altitude of the water level in wells 4 and 10 for different times. Well 10 is 2,120 feet from the effective center of pumping of wells of group I. During the period 8:00 a.m., June 8, to 8:00 a.m. June 20, when the wells of group I were being pumped at an average rate of 644 gallons a minute, the water level in well 10 declined from 51.51 feet to 61.33 feet below sea level. Furthermore, when pumping was increased on June 20 by the pumping of wells 2, 5, and 7 the water level declined still further--to 72.50 feet below sea level at 1:00 p.m. June 30.

Figure 9 shows in graphic form the effect on the water level in the various wells caused by the pumpage from wells of group I during the period June 8 - July 10, 1938. The mean corrected water level curves for the same period are shown in Figure 10. The additional effect created by pumping well 11 is shown in the mean corrected water level curves given in figure 11.

Effect of pumping tests at Indian Head on water level in outcrop area in Virginia.

During the course of the pumping tests on the wells at Indian Head, careful measurements were made of the depth to the water levels in selected wells situated in the outcrop area in Virginia of the formations tapped by the wells at Indian Head. These measurements are shown graphically in figure 13. Measurements were also obtained during the period of the Indian Head tests of the fluctuations of the water levels in wells at the Marine Corps Reservation at Quantico, Va. (see figure 6). In spite of the extended duration of the tests at Indian Head no measurable effect in the observation wells in Virginia could be found that could be attributed to the operation of the Indian Head wells.

Most of the wells observed in Virginia at the time of the Indian Head tests were found to fluctuate in response to changes in the tide in the Potomac River and the tidal estuaries tributary thereto. The effect of pumping wells on the Marine Corps Reservation was discernible in other nearby wells as was to be expected. If there was at any time any response to pumping at Indian Head, the effect was so small that it was completely obscured by greater fluctuations caused by changes in tide, pumping, atmospheric pressure, or rainfall. Furthermore there was no field evidence obtained to indicate that there had been any lowering of the water levels in the outcrop area, in Virginia, of the formations tapped by the Indian Head wells, that was caused by the pumping that had been done thus far at Indian Head since the beginning of major pumping on the reservation.

Coefficients of transmissibility and storage of the water-bearing beds.

The transmissibility of a water-bearing bed, or aquifer, is a measure of its ability to transmit water. The coefficient of transmissibility is defined as the rate of flow, in gallons a day, through a vertical strip of the aquifer from top to bottom, one foot wide, under a hydraulic gradient of unity.

It is the coefficient of permeability, as defined by Meinzer,[/] multiplied by

[/] Grover, N. C., Contributions to the hydrology of the United States, Water-Supply Paper 596, p. 148.

the thickness of the aquifer, in feet.

The coefficient of storage is a measure of the amount of water removed from storage through compression of the aquifer by the weight of the overlying beds as the hydrostatic pressure within the aquifer is reduced. It is defined as the volume of water, in cubic feet, released from storage in a column of the aquifer having a base 1 foot square, when the piezometric or pressure surface is lowered 1 foot.

These two factors - transmissibility and storage - largely determine for a given rate of pumping the rate of expansion, the areal extent, and the depth of the "cone of influence" around a well or group of wells. Thus, it is theoretically possible, within certain limitations, to determine the quantity of water that may be recovered by a given system of wells from the values of these coefficients.

The theoretical approach to the problem of determining the quantity of water that can be recovered from wells involves first, the determination of average values for the coefficient of transmissibility and the coefficient of storage, and second, the application of these average values to postulated well systems. Several methods are generally used for determining coefficients of transmissibility and storage in order to provide a series of checks on the applicability of the basic data. The range in coefficients determined thus by the different methods reflects chiefly the degree of variation of the conditions found in nature from the ideal conditions on which the methods are based. Several methods may likewise be used in studying the effects of hypothetical well systems.

A brief description of the different methods used to determine the coefficients of transmissibility and storage of the water-bearing beds, with computed values for the coefficients and a tabulation of the base data, are given in the appendix to this report.

Significance of the coefficients as determined by the different methods.

A summary of the values of the coefficients of transmissibility (T) and storage (S) as computed by the different methods is given in the following table. In all of the methods it is assumed that the aquifer is homogeneous, constant in thickness, and of infinite areal extent. It is further assumed that the pumped well is screened the entire thickness of water-bearing beds penetrated by the observation wells, and that the well is pumped at a constant rate or in sequences of constant rates, the changes in rates occurring instantaneously.

Table 9. Summary of determinations of coefficients of transmissibility and storage by various methods.

Pumping test on:	Method	Period of test	Coefficient of transmissibility T	Coefficient of storage S
Well 11	Thiem		2,310	---
	Theis recovery		1,770	---
	Graphical		2,590	4.42×10^{-4}
Group I	Thiem	II	3,130	---
		III	1,980	---
	Graphical	II	4,210	3.76×10^{-4}
		III	4,020	2.95×10^{-4}
	Maximum slope	II	---	5.38×10^{-4}
		III	---	4.24×10^{-4}

The equilibrium of water levels, assumed for the method developed by Thiem is not fully attained so long as water is being drawn from storage in any part of the aquifer. Until absolute equilibrium is established, observed differences in drawdown may be somewhat less than corresponding differences in drawdown at equilibrium, and if so, the values of transmissibility determined by the Thiem method will be somewhat too large by an amount depending on the respective distances of the observation wells from the pumped well and on the time elapsed since pumping began. However, as pointed out by Wenzel,[/] the cone of influence

[/] Wenzel, L. K., The Thiem method for determining permeability of water-bearing material: Geol. Survey Water-Supply Paper 679, p. 51, 1936.

in the vicinity of a pumped well will ultimately reach a condition of approximate equilibrium--that is, the cone will reach a form that will remain practically unchanged although the water levels will continue to decline. Hence the differences in drawdown of the water levels in observation wells situated within the part of the cone of influence that has, for a given period of pumping, reached an approximate equilibrium form will remain practically unchanged with continued pumping, and the coefficients of transmissibility computed therefrom by the Thiem formula will be virtually the same. It is of the utmost importance for the application of the Thiem method that the observation wells be within the part of the cone that has reached an essential equilibrium form, as otherwise, the computed coefficients will decrease with continued pumping.

Although the water-bearing formations underlying Indian Head are believed to be "fairly continuous and of more or less uniform thickness,"[/] there doubtless

[/] Fiedler, A. G., Cady, R. C., Meinzer, O. E., Op. cit., p. 10.

are lateral variations in permeability and in the thickness of the aquifer that may account for the computation of larger coefficients of transmissibility from the test on wells of group I than from the test on well 11. Furthermore, well 11 may not tap all of the water-bearing beds tapped by the several wells of group I. However, the log of well 11 is not available; hence this cannot be verified directly. It is believed that values of transmissibility (T) and storage (S) determined from the test on wells of group I are more truly representative of the characteristics of the aquifer as a whole than the values obtained from the tests on well 11.

The value of transmissibility determined by the modified Thiem method for the second period of the test on wells of group I is 3,130 and, using the same observation wells, that for the third period is 1,980. The difference between the two values is believed to be due to the failure of the cone of influence to reach an equilibrium form corresponding to the "effective average" pumping rates at which the tests were run.

The remaining values of the coefficient of transmissibility (T) as determined from the tests on group I are 4,210 for the second period and 4,020 for the third period. These values were obtained by the graphical method. On the basis of analyses of the applicability of the several methods to the tests, it is believed that the values computed by the graphical method from the tests on wells of group I are more accurate than the values computed by the other methods. Accordingly 4,000 is used in this report as the coefficient of transmissibility. This indicates that 4,000 gallons a day will percolate through each vertical strip of the aquifer one foot wide under a hydraulic gradient of unity.

The coefficient of storage (S) is a function of the porosity and thickness of the aquifer and the elastic moduli of the water and of the aquifer. Because of lateral variations in porosity and thickness of the aquifer, it is to be expected that values of the coefficient of storage computed from water-level data for different wells by the graphical method will also vary.

The average coefficient of storage determined by the graphical method is 3.76×10^{-4} for the second period of the pumping test on wells of group I (see table 9) and 2.95×10^{-4} for the third period. The coefficient determined by the maximum slope method is 5.88×10^{-4} for the second period and 4.24×10^{-4} for the third period. The coefficient of storage to be used for predicting long-time trends should theoretically be somewhat smaller than that determined by the maximum-slope method. In the following computations a coefficient of

3.7×10^{-4} is used. This indicates that 3.7×10^{-4} cubic feet (0.00037 cubic foot) of water will be released from storage in each vertical column of the aquifer having a base of 1 foot square when the head of the water is lowered 1 foot.

Quantity of water that can be obtained from wells at Indian Head.

A theoretical method for determining the nature of the cone of depression created in ground-water bodies by pumping from wells has been developed by Theis.[1] The assumed conditions are not usually found in nature, and thus the

[1] Theis, C. V., The significance and nature of the cone of depression in ground-water bodies, Econ. Geol. Vol. XXXIII, No. 8, pp. 889-902, Dec. 1938.

method is not strictly applicable to natural conditions. Nevertheless, the method is of value in giving approximate results. These results, in turn, provide a reasonably satisfactory basis for estimating the perennial yield of the water-bearing beds.

The procedure followed in the mathematical treatment of the problem, as devised by Theis, is intricate and involves an extensive series of computations. The mathematical discussion and detailed computations are not given in this report but the results are presented herewith.

The water available to wells at Indian Head is derived from that part of the precipitation on the outcrop area in Virginia which seeps into the ground and percolates down the dip of the water-bearing beds. The quantity of water obtainable by wells depends in part on the cross-sectional area of the beds through which the water is transmitted to the wells. Therefore, in order to draw water from the maximum cross-sectional area of the water-bearing beds, additional wells at Indian Head should be distributed as widely as the physical limits of the reservation will permit. This condition is theoretically met by the installation of wells at three additional sites along a line running northeast-southwest, as shown in figure 3. Additional water could be developed from wells on Federal property on Stump Neck to the south and on nearby private property to the north of the reservation, but it is believed that the perennial supply so obtained would be comparatively small.

The wells that now supply the water for the reservation are designated group I in figure 3 and the stand-by wells near the acid plant are designated group II. The postulated wells are shown in the figure at sites III, IV, and V. The installation at each of the new sites is assumed to consist of one or more wells that, regardless of location, number and diameter, are equivalent in yield and effect to the present installation at group I.

Water-bearing beds tapped by the wells at Indian Head are from 153 feet to 363 feet below sea level, and it is believed that a drawdown of 215 feet below sea level is about the maximum permissible. Such a drawdown would unwater the upper part of the formation and would reduce the cross-sectional area of saturated material. A drawdown greater than 215 feet is, of course, physically possible, but it probably would not produce any great additional yield.

Computations based on the theoretical installations indicated in figure 3, using a coefficient of transmissibility of 4,000 and a coefficient of storage of 3.7×10^{-4}, give the following results for the maximum perennial yield of the respective groups:

Maximum perennial yield of wells at Indian Head

Group	I	I, II	I, II, III, IV, V
Million gallons a day	1.07	1.43	2.80
Gallons a minute	740	990	1,940

at site I, 222 feet at site II, and 187 feet at sites III, IV and V. The variation in the above permissible levels is accounted for by the difference in the depth to the water-bearing beds at the respective sites.

The investigation shows that a supply of 12 million gallons a day, as was initially indicated to the Geological Survey as the quantity desired, can not be obtained. The data indicate that a perennial yield of about three million gallons a day can be developed and that somewhat larger quantities can be pumped during short periods.

Quality of water from wells and from the Potomac River

By W. D. Collins

In connection with the studies of the quantity of ground water available at Indian Head, several samples were collected for analysis at the beginning of the work in June 1937, and another series of samples was taken from July 19 to July 27, 1938. The results of examination of the samples collected in July 1938 are given in table 10.

Analyses of samples collected at different times from neighboring points in Maryland and Virginia indicate that the ground water in a considerable area around Indian Head has about the same composition as the water in the wells for which analyses are given in the table. This water carries in solution about 200 parts per million of mineral matter, which consists very largely of sodium bicarbonate. The only other constituent that approaches the sodium or bicarbonate is the silica. The water has practically no hardness.

By almost any standards the water would be classed as excellent for all ordinary uses, so far as such uses are affected by the dissolved mineral matter. Analyses made by the Geological Survey and by others over a considerable period of time do not suggest any probability of change in composition of the water furnished by the wells under any probable program of use.

If more water must be used than can be supplied by wells, the Potomac River is the obvious and the only practicable source from which to take the additional supply. The quality of the river water during most of the time is acceptable as regards its dissolved mineral matter. The water is, however, nearly always sufficiently turbid to require filtration before use in the manufacturing processes. The treatment needed to render the river water satisfactory for manufacturing can easily be designed to make the water safe to drink, even though the river receives from Alexandria, Va., untreated sewage and from Washington, D. C., partially treated sewage.

Table 10.--Analyses of ground water at the Naval Powder Factory, Indian Head, Md.

Analyzed by Margaret D. Foster — Parts per million

Well number	1	2	5	6	7	8	9	12	13
Silica (SiO_2)	42	--	--	--	--	36	--	26	--
Iron (Fe)	.06	--	--	--	--	.05	--	.10	--
Zinc (Zn)	1.0	--	--	--	--	.0	--	2.0	--
Calcium (Ca)	1.0	--	--	--	--	1.1	--	1.5	7.9
Magnesium (Mg)	.6	--	--	--	--	.6	--	.4	5.8
Sodium (Na)	65	--	--	--	--	60	--	72	74 (Na + K)
Potassium (K)	2.1	--	--	--	--	2.0	--	2.2	
Bicarbonate (HCO_3)	155	160	146	149	155	144	150	169	210
Sulphate (SO_4)	12	8	17	13	10	13	11	11	2.1
Chloride (Cl)	7.6	13	6.0	2.0	9.0	4.3	5.0	11	20
Fluoride (F)	1.0	--	--	--	--	1.0	--	1.1	.6
Nitrate (NO_3)	.47	--	--	--	--	.58	--	.62	.25
Total dissolved solids	210	--	--	--	--	192	--	211	--
Total hardness as $CaCO_3$	6.5	(a)	(a)	(a)	(a)	5.2	(a)	8.4	44
Date of collection (1938)	July 19	July 19	July 19	July 20	July 19	July 19	July 19	July 27	July 27

a/Less than 5 parts per million.

The most extensive collection of information on the composition of the Potomac River water is in the records of the Dalecarlia filtration plant of the District of Columbia. Regular analyses of the raw water as taken from the river for treatment show the quantities of dissolved and suspended matter in the river above Great Falls. Very little occurs to change the content of dissolved mineral matter between Great Falls and Indian Head, so that the dissolved mineral matter at Indian Head may be assumed to be practically the same as at Great Falls, except for periods when the composition of the water is affected by salt water from Chesapeake Bay. More comprehensive analyses than are regularly made at the Dalecarlia filtration plant were made by Margaret D. Foster in 1921 for use in Geological Survey Water-Supply Paper 496, "The industrial utility of public water supplies in the United States." These analyses were of composites of about 10 daily samples each. The average and the analyses corresponding to the maximum and the minimum hardness are given in table 11.

The Geological Survey has made no investigations of the sanitary condition of the river since the preparation of Water-Supply Paper 192 in 1907. The Public Heath Service has, however, made studies of conditions in the river in 1916 and again in 1933. The results of these studies will be available to anyone who may have to design a plant for treatment of the river water at Indian Head.

From the point of view of the needs of the Naval Powder Factory, the Potomac River may be considered to furnish an inexhaustible supply. There seems to be no probability that any possible future regulation of the flow of the river would decrease the quantity of water flowing past Indian Head to a point where the quantity would be inadequate for the use of the Powder Factory.

The main problem with reference to the use of the Potomac River water as a source of supply is the extent to which the river water at Indian Head will be contaminated with salt water from Chesapeake Bay. The distance to which salt water comes up the river depends upon the flow of the river, the tides, and,

Table 11.—Analyses of dissolved mineral matter in composites of daily samples of Potomac River water at Great Falls, Md.

Analyzed by Margaret D. Foster - Parts per million			
Date of collection (1921)	Average January 1-December 31	November 1-10	March 11-20
Silica (SiO_2)...........	6.6	3.8	8.1
Iron (Fe)...............	.07	.10	.06
Calcium (Ca)............	23	34	15
Magnesium (Mg)..........	5.4	8.1	3.6
Sodium (Na).............	3.0	3.6	2.1
Potassium (K)...........	1.4	2.2	1.0
Bicarbonate (HCO_3)......	70	110	39
Sulphate (SO_4)..........	20	26	17
Chloride (Cl)...........	3.3	5.0	2.6
Nitrate (NO_3)...........	2.8	1.4	3.2
Total dissolved solids...	103	140	77
Total hardness as $CaCO_3$..	80	118	52

to some extent, the wind. No comprehensive studies of this question have ever been made. In connection with studies of the river made in 1912 by the Bureau of Chemistry of the Department of Agriculture, with reference to the safe limits for taking oysters from the river and bay, the chloride in surface and bottom samples was determined on several occasions. At times a small increase in chloride above that normal to the river was found at Indian Head.

Determinations of chloride in the river water have been made at the Chemical Laboratory of the Naval Powder Factory at various times from 1913 to 1938. Of eleven samples tested from 1913 to 1925, only three had more than 100 parts per million of chloride, and the largest quantity found in any of these samples was 239 parts per million. During a prolonged period of low water in 1930 and 1931, the chloride content ranged from 589 parts per million August 9, 1930, up through 3,218 parts per million November 12, 1930, and to 642 parts April 7, 1931. On April 27, 1931, the chloride was only 39 parts per million, but in a sample collected December 28, 1931, it was 1,389 parts.

These scattered observations indicate that there is likely to be a period of at least a few days every year when the chloride concentration in the river water at Indian Head will be sufficient to be objectionable. In some years this condition may persist over several months under present conditions. If in the future some form of regulation of flow should be put into effect, the lowest flow might be kept well above the minimum that will occur if the flow is not regulated.

Mention has been made of Mattawoman Creek as a possible source of additional supply. The character of the water at the mouth of the creek must be about like that of the river for most of the time. Away from the influence of the river the creek water would be expected to carry less dissolved mineral matter and to be decidedly colored. The treatment for use in manufacturing would not be very different from the treatment required for the river water.

At times when the river water at Indian Head is unsuitable for use there is doubt as to whether the creek would furnish a sufficient quantity of water. There appears to be little chance for storage of water from Mattawoman Creek to provide for periods of low flow.

Conclusions and Recommendations.

The investigations of the ground-water conditions at Indian Head lead to the conclusion that the perennial yield from the wells of group I (Pumphouse No. 1) is about one million gallons a day and that the combined perennial yield from wells of groups I and II (Pumphouses No. 1 and No. 2) is about one and one-half million gallons a day. If additional widely distributed wells are installed on the main station grounds, it is likely that the perennial yield of all the wells will be about three million gallons a day.

If an additional supply of ground water is to be developed, it is recommended that wells be constructed at each of the three sites (III, IV, and V, in figure 3), and possibly at intermediate points, and that the new wells be of gravel-wall construction unless coarse water-bearing material is encountered. The drilling of additional wells on Stump Neck or on private property north of the reservation would increase the perennial yield. The increase in yield that could be obtained by drilling wells outside the reservation on an extension of the line connecting the postulated wells at sites III and V, assuming the geologic and hydrologic conditions to be the same as those at the reservation, would be proportionately somewhat less than the increase in the length of the line connecting the wells.

Because the ground-water supply is inadequate to meet the demand in the event that manufacturing operations are greatly expanded, consideration should be given to plans for the use of surface water. The Potomac River would furnish water in sufficient quantity for all needs. However, the river water is at times so high in chloride as to be unfit for the desired use at the factory. The periods of high chloride apparently range from only a few days to several months, as in the exceptionally dry period of 1930 and 1931. If a surface-water supply is installed, it will, therefore, be necessary to make provision for periods of high chloride. The following means for meeting these emergency conditions may be considered:

1. Maximum use of water from wells.
2. Use of water from Mattawoman Creek, with or without a dam.
3. Storage of water from wells or from the river in reservoirs provided for the purpose.
4. Dilution of river water when it is objectionably high in chloride.
5. Economy in the use of water and re- using of the water where practicable.

Should a supply from the Potomac River be seriously considered, an investigation should be made of the chemical character of the river water. In order to learn the relation between river discharge and the amount of salt-water contamination a comprehensive study must be made of the movement of salt water up and down the river. An investigation of the movement of salt water will involve studies of distribution of salt water throughout the section of the river at points where there is appreciable salt-water contamination, and careful studies to determine proper points for continuous sampling. The salinity survey would be needed also to determine the most advantageous place for the intake or intakes as to their position in the cross-section and as to their distance above Indian Head. If the Mattawoman Creek is considered as a source of supply, it would be desirable to install a gaging station on it and to make a series of analyses of composites of daily samples of water.

It is recommended that the recording gages installed during this investigation be continued in operation indefinitely and that records of the quantity of water pumped from wells be continued.

APPENDIX

By C. E. Jacob

Computation of coefficients of transmissibility and storage

Test of well 11 of Group II

Determination of coefficient of transmissibility

Thiem method.-It is theoretically possible by means of the Thiem method to determine the transmissibility of an aquifer from observations of the drawdown produced in two wells situated at different distances from a pumped well that penetrates the same aquifer and discharges at a known rate. The equation for transmissibility based on the Thiem method is as follows:

$$T = \frac{527.7\ Q \log_{10} \frac{r_n}{r_m}}{z_n - z_m}$$

T is the coefficient of transmissibility of the aquifer, in gallons a day for each foot of width of the aquifer. It is equal to the product of the coefficient of permeability by the thickness of the beds.

Q is the pumping rate, in gallons a minute.

z_m and z_n are the respective drawdowns at two observation wells in feet.

r_m and r_n are the respective distances of the observation wells from the pumped wells, in feet.

The derivation of the above equation and the method of its application have been discussed in some detail by Wenzel.[1/]

The Thiem equation is based on the assumption that equilibrium has been established in the sense that the lowering of the water levels in observation wells in the vicinity of the pumped well is proceeding at essentially a uniform rate. In computing the drawdown produced in each well by pumping well 11, only the first of the two periods of the test was considered. Pumping began at 1:22 p.m., on July 11, and by 8:40 a.m., July 15, equilibrium was

1/Wenzel, L. K., The Thiem method for determining permeability of water-bearing materials and its application to the determination of specific yield, results of investigations in the Platte River Valley, Nebr., U.S. Geol. Survey Water-Supply Paper 679a.

reasonably well established, so as to permit application of the Thiem method. After that time, however, equilibrium conditions were disturbed by the sudden increase in the pumping rate. Therefore, in applying the Thiem method, the drawdown produced in any well was considered to be the difference between the altitude of the water level at the beginning and at the end of the first period, and in computing the coefficient of transmissibility, a value of 64.8 was used for Q.

Table 12 gives the drawdown observed in each of the four observation wells, and the computations of coefficients of transmissibility for all possible combinations of the observation wells. The average of the values of transmissibility thus determined is seen to be 2,310, which means that when the hydraulic gradient is unity the flow through a vertical strip of the aquifer one foot wide would be 2,310 gallons a day.

Theis recovery method.-When the pump on a well is shut down, the water level in the well rises--rapidly at first, and then at a continiually decreasing rate.

Table 12. Data obtained from the pumping test on well 11 for determining the coefficient of transmissibility by the Thiem method.

Well	Distance from pumped well (No. 11), in feet	Altitude of water level, in feet, (datum mean sea level) at 1:22 p.m. July 11, 1938	at 8:40 a.m. July 15, 1938	Drawdown, in feet
10	256	-69.96	- 85.45	15.49
12	356	-67.05	- 78.73	11.68
14	1,080	-55.33	- 59.94	4.61
4	2,050	-135.97	-137.61	1.81

Wells m	n	r_n/r_m	$Log_{10} r_n/r_m$	$(z_m - z_n)$	Coefficient of transmissibility T
10	12	1.39	0.143	3.81	1,250
10	14	4.22	0.626	10.88	1,970
10	4	8.00	0.903	13.68	2,250
12	14	3.04	0.483	7.07	2,340
12	4	5.76	0.761	9.87	2,640
14	4	1.90	0.279	2.80	3,410
Aver.					2,310

The difference between the recovering water level at a given instant after shut-down and the static water level is termed the "residual drawdown." Theis [/] has shown that the transmissibility of the aquifer may be determined,

[/] Theis, C. V., The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage. Transactions Amer. Geophysical Union, 16th Ann. meeting, pp. 519-524, 1935.

The significance and nature of the cone of depression in ground-water bodies, Econ. Geology, Vol. XXXIII, pp. 889-902, Dec., 1938.

within certain limits, by plotting the residual drawdown against the log of the ratio between the time elapsed since pumping started and the time elapsed since pumping stopped. The equation expressing the coefficient of transmissibility as a function of these factors is as follows: $T = \frac{264\ Q \log_{10} \frac{t}{t'}}{Z}$ where T is the coefficient of transmissibility, as before; t is the time since pumping started and t' the time since pumping stopped; Z is the residual drawdown, in feet; and Q is the rate of discharge of the well before shut-down, in gallons a minute.

As the length of the pumping period was 5,879 minutes, the time since pumping started (t) is 5,879 + t'. The average rate of discharge from the beginning of pumping until shut-down, covering both periods of the test (Q) was 67.1 gallons a minute. Thus,

$$T = \frac{17{,}700 \log_{10} \frac{5{,}879 + t'}{t'}}{Z}$$

As pumping is continually in progress at Indian Head, static water level could not be determined. Therefore, the following modified form of the equation is used:

$$T = \frac{17{,}700 \left[\log_{10} \frac{5{,}879 + t'_1}{t'_1} - \log_{10} \frac{5{,}879 + t'_2}{t'_2}\right]}{Z_2 - Z_1}$$

If t'_1 and t'_2 are so chosen that

$$\frac{5{,}879 + t'_1}{t'_1} = 10 \left[\frac{5{,}879 + t'_2}{t'_2}\right]$$

then for such values the coefficient of transmissibility (T) becomes $\frac{17{,}700}{Z_2 - Z_1}$.

The coefficient of transmissibility may therefore be determined by use of the graph shown in figure 14. In this graph the coefficient of transmissibility is equal to the horizontal projection ($Z_2 - Z_1$) of that part of the straight line drawn through the plotted points which is intercepted, for example, by the lines t/t' = 1 and t/t' = 10 (or 10 and 100).

The observational data resulting from the test on well 11, as given in table 13, are shown in figure 14 by a solid line and the dashed line therein is the mean curve. The difference in residual drawdown, Z_2-Z_1, to be used in the formula, is determined by measuring the intercept of values of t/t' of 1 and 10, or 10 and 100, respectively. It happens that the value of $Z_2 - Z_1$, as thus determined, is about 10. Substituting in the equation $\frac{17,700}{Z_2 - Z_1}$, the coefficient of transmissibility (T) is computed to be 1,770.

Determination of coefficients of transmissibility and storage by graphical method.

By recourse to the analogy between the flow of heat and the flow of water through a homogeneous aquifer from which "a specific amount of water is discharged instantaneously from storage as the pressure falls", Theis[1] has

[1] Theis, C. V., op. cit.

shown that the drawdown, Z, in feet, at a point r feet distant from a well which has been pumped for t days at a constant rate of Q gallons a minute may be determined from the formula:

$$Z = \frac{114.6\,Q}{T}\,W(u)$$

The factor W (u) is designated the "well function" by Theis and is equal to $-0.577216 - \log_e u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \frac{u^4}{4.4!}$ .... The symbol u equals $\frac{1.87\,r^2\,S}{Tt}$, where the symbols have the same meaning as previously, and S is the coefficient of storage. The coefficient of storage is defined as the volume of water, measured in cubic feet, released from storage in each column of the aquifer having a base 1 foot square when the head of the water is lowered 1 foot.

Table 13. Determination of coefficient of transmissibility from recovery of the water level in well 11, July 15, to 19, 1938

Date 1938	Hour	Altitude of water level, in feet, datum mean sea level	Residual drawdown, -s, in feet	Time since pumping stopped, t' in minutes	$\frac{5,879 + t'}{t'}$
July 15	3:21 p.m.	-	-	0	-
	3:23	-107.67	36.95	2	2,940
	3:24	-103.27	32.55	3	1,961
	3:27	- 98.57	27.85	6	981
	3:30	-97.10	26.38	9	654
	4:00	-91.88	21.16	39	152
	4:30	-89.72	19.00	69	86.2
	5:00	-88.24	17.52	99	60.4
	5:30	-87.04	16.32	129	45.5
	6:00	-86.11	15.39	159	36.0
	7:00	-84.65	13.93	219	26.8
	8:00	-83.55	12.83	279	22.1
	9:00	-82.60	11.88	339	18.3
	10:00	-81.80	11.08	399	15.7
	11:00	-81.20	10.48	459	13.8
	12:00	-80.60	9.88	519	12.3
16	2:00 a.m.	-79.75	9.03	639	10.2
	4:00	-79.08	8.36	759	8.75
	6:00	-78.52	7.80	879	7.69
	8:00	-78.07	7.35	999	6.89
	10:00	-77.65	6.93	1,119	6.25
	12:00	-77.29	6.57	1,239	5.75
	6:00 p.m.	-76.38	5.66	1,599	4.67
	12:00	-75.70	4.98	1,959	4.00
17	6:00 a.m.	-75.14	4.42	2,319	3.54
	12:00 m.	-74.71	3.99	2,679	3.20
	6:00 p.m.	-74.33	3.61	3,039	2.94
	12:00	-74.01	3.29	3,399	2.73
18	12:00 m.	-73.50	2.78	4,119	2.42
	12:00	-73.13	2.41	4,839	2.22
19	12:00 m.	-72.83	2.11	5,559	2.06

Values of W(u) are available in tabular form _/ for a limited range of the argument, where the values to be used are those given for Ei (-x), with the

_/ Smithsonian physical tables, 8th rev. ed., table 32, 1933, Jøhnke and Emde, Funktionentøfeln, 2nd rev. ed., pp. 83-85, 1933.

sign changed. Values ranging from u = 1 to u = 10^{-7} have recently been computed by C. E. Jacob.

Inasmuch as the above equation takes into consideration the factor of time, it is a "non-equilibrium" equation, in contrast to the Thiem equation, which assumes that the piezometric surface has essentially an equilibrium form.

By means of a graphical method devised by Theis, _/ the non-equilibrium

_/ Theis, C. V., Memorandum on Indian Head investigation as interpreted according to pumping test formulae, unpublished manuscript, Files of Geol. Survey, 1938.

equation is applied to determine the coefficients of transmissibility and storage from water-level observations in one or more of the wells. The method consists primarily of plotting, in logarithmic coordinates, for each well, the values of the observed drawdown against corresponding values of $\frac{r^2}{t}$. The curves thus obtained are matched with a "type curve", which is a graph of the "well function" [W(u)], against corresponding values of u plotted to the same logarithmic scale.

In tables 14 a, b, c, and d, values of $\frac{r^2}{t}$ are given for wells 10, 12, 14/ and 4, respectively. These data are plotted in figure 15 and are based on points taken at various intervals from the corrected drawdown curves shown in figure 6.

The values of the coefficients of transmissibility and storage based on the data for the respective wells are shown in table 14. The average value of the coefficient of transmissibility resulting from the application of this method is 2,590, and the average value of the coefficient of storage is 4.42 x 10^{-4}.

Table 14. Determination of coefficients of transmissibility and storage by graphical method involving application of non-equilibrium equation. Test on well 11, July 11 to 15, 1938.

	Points representing best fit of curves to type curve				Coeff. of transmissibility	Coeff. of storage
Well	r^2/t $(x10^3)$	Z	u	W(u)	T	S
10	0.627	12.0	0.01	4.05	2,510	2.14×10^{-4}
12	0.582	10.0	0.02	3.36	2,500	4.59
14	3.72	4.00	0.20	1.22	2,270	6.55
4	14.80	1.70	0.40	0.70	3,060	4.42
Aver.					2,590	4.42×10^{-4}

Table 14a. Well 10, r^2 = 65,500

Date 1938	Hour	Altitude of water level, in feet, datum mean sea level	Time since pumping began, t, in days	r^2/t	Draw-down, in feet
July 11	2 p.m.	-72.79	0.026	2,520,000	2.83
	3	-74.63	0.068	963,000	4.67
	4	-75.70	0.109	600,000	5.74
	5	-76.45	0.151	434,000	6.49
	1:22 p.m.	-69.96	0		0
	6	-77.10	0.193	339,000	7.14
	12	-79.34	0.443	148,000	9.38
12	6 a.m.	-80.61	0.693	94,500	10.65
	12 m.	-81.53	0.943	69,500	11.57
	6 p.m.	-82.23	1.193	54,900	12.27
	12	-82.80	1.443	45,400	12.84
13	6 a.m.	-83.27	1.693	38,600	13.31
	12 m.	-83.67	1.943	33,700	13.71
	6 p.m.	-84.02	2.193	29,900	14.06
	12	-84.32	2.443	26,800	14.36
14	6 a.m.	-84.59	2.693	24,300	14.63
	12 m.	-84.82	2.943	22,200	14.86
	6 p.m.	-85.03	3.193	20,500	15.07
	12	-85.22	3.443	19,000	15.26
15	6 a.m.	-85.38	3.693	17,700	15.42

Table 14b Well 12, r^2 = 126,700

Date 1938	Hour	Altitude of water level, in feet, datum mean sea level	Time since pumping began, t, in days	r^2/t	Drawdown, in feet
July 11	2 p.m.	-67.90	0.026	4,870,000	0.85
	3	-68.90	0.068	1,860,000	1.85
	4	-69.65	0.109	1,160,000	2.60
	5	-70.22	0.151	839,000	3.17
	1:22 p.m.	-67.05	0		0
	6	-70.72	0.193	656,000	3.65
	12	-72.67	0.443	286,000	5.62
12	6 a.m.	-73.81	0.693	183,000	6.76
	12 m.	-74.63	0.943	134,000	7.58
	6 p.m.	-75.28	1.193	106,000	8.23
	12	-75.81	1.443	87,800	8.76
13	6 a.m.	-76.28	1.693	74,800	9.23
	12 m.	-76.67	1.943	65,100	9.62
	6 p.m.	-77.04	2.193	57,800	9.99
	12	-77.37	2.443	51,800	10.32
14	6 a.m.	-77.67	2.693	47,000	10.62
	12 m.	-77.95	2.943	43,000	10.90
	6 p.m.	-78.20	3.193	39,700	11.15
	12	-78.44	3.443	36,800	11.39
15	6 a.m.	-78.66	3.693	34,300	11.61

Table 14c. Well 14, r^2 = 1,166,000

Date 1938	Hour	Altitude of water level, in feet, datum mean sea level	Time since pumping began, t, in days	r^2/t	Drawdown, in feet
July 11	2 p.m.	-55.39	0.026	44,800,000	0.06
	3	-55.46	0.068	17,100,000	0.13
	4	-55.52	0.109	10,700,000	0.19
	5	-55.60	0.151	7,710,000	0.27
	1:22 p.m.	-55.33	0		0
	6 p.m.	-55.67	0.193	6,040,000	0.34
	12	-56.08	0.443	2,630,000	0.75
12	6 a.m.	-56.48	0.693	1,680,000	1.15
	12 m.	-56.86	0.943	1,240,000	1.53
	6 p.m.	-57.22	1.193	976,000	1.89
	12	-57.57	1.443	808,000	2.24
13	6 a.m.	-57.89	1.693	689,000	2.56
	12 m.	-58.19	1.943	600,000	2.86
	6 p.m.	-58.47	2.193	532,000	3.14
	12	-58.72	2.443	477,000	3.39
14	6 a.m.	-58.97	2.693	434,000	3.64
	12 a.m.	-59.21	2.943	396,000	3.88
	6 p.m.	-59.43	3.193	365,000	4.10
	12	-59.63	3.443	338,000	4.30
15	6 a.m.	-59.85	3.693	316,000	4.52

Table 14d. Well 4, $r^2 = 5,202,500$

Date 1938	Hour	Altitude of water level, in feet, datum mean sea level	Time since pumping began, t, in days	r^2/t	Drawdown, s, in feet
July 11	1:22 p.m.	-135.97	0		0
	6 p.m.	-135.99	0.193	27,000,000	0.02
	12	-136.06	0.443	11,700,000	0.09
12	6 a.m.	-136.17	0.693	7,500,000	0.20
	12 m.	-136.30	0.943	5,520,000	0.33
	6 p.m.	-136.44	1.193	4,350,000	0.47
	12	-136.60	1.443	3,600,000	0.63
13	6 a.m.	-136.74	1.693	3,070,000	0.77
	12 m.	-136.89	1.943	2,680,000	0.92
	6 p.m.	-137.02	2.193	2,370,000	1.05
	12	-137.14	2.443	2,130,000	1.17
14	6 a.m.	-137.27	2.693	1,930,000	1.30
	12 m.	-137.40	2.943	1,770,000	1.43
	6 p.m.	-137.52	3.193	1,630,000	1.55
	12	-137.63	3.443	1,510,000	1.66
15	6 a.m.	-137.76	3.693	1,410,000	1.79

Tests of wells of group I

Effective average pumpage rates

The equations used in determining coefficients of transmissibility and storage are based on the assumption that pumpage is maintained at a constant rate. When such is not the case, corrections must be made to weight the pumpage to determine "effective average" rates which might then be applied to water-level measurements made during a test to determine coefficients of transmissibility and storage.

During the first period of the test on wells of group 1 the pumpage rate was maintained fairly constant at an averaging rate of 644 gallons a minute, and therefore the average rate may be considered to be the "effective average." However, during the second period of the test the rate of pumping declined from 907 gallons per minute at first to 753 gallons per minute at the close of the test, and during the third period the rate increased from an initial rate of 663 gallons per minute to a maximum of 728 gallons per minute 11 days later, and declined thereafter. The "effective average" rates of pumping for these periods were, therefore, computed by weighting the pumpage according to time and by taking into consideration the effect of change in pumping rate on the drawdown of the water level in well 10.

The effective average rates of pumping for different periods are shown in column "Q" of table 15.

Determination of coefficient of transmissibility by the Thiem method.

According to the Thiem equation, the difference in drawdown, in feet, in two observation wells located r_m and r_n feet from a pumped well is shown by the following equation:

$$Zm - Zn = \frac{527.7\ Q \log_{10} \frac{r_n}{r_m}}{T},$$

where Q is the rate of discharge of the pumped well, in gallons a minute, and where T is the coefficient of transmissibility as previously defined.

the approximate geometrical center of the pumped wells of group I. Values of T computed from drawdowns measured at 8 a.m., June 20, and at 11 a.m., June 30, are given in table 15a and those computed from drawdowns measured at 11 a.m., June 30, and 1:22 p.m., July 11, in table 15b. The average of the computed coefficients of transmissibility is 2,560.

Determination of coefficients of transmissibility and storage by modified graphical method.

If a well is pumped at a constant rate of Q gallons a minute, the drawdown in a well r feet distant from the pumped well follows the relationship

$$Z = \frac{114.6\ Q}{T}\ W\left(\frac{1.87r^2S}{Tt}\right)$$

where t is the time in days since pumping began and the other factors have the same meaning as previously.

If after a certain time the rate of pumping is instantaneously increased by a finite amount ΔQ_1 and maintained at the constant rate $(Q + \Delta Q_1)$, a second, lower limb of the drawdown curve is obtained which follows the relationship.

$$Z = \frac{115\ Q}{T}\ W\left(\frac{1.87r^2S}{Tt}\right) + \frac{115\,\Delta Q_1}{T}\ W\left(\frac{1.87r^2S}{Tt'}\right)$$

Here t' is the time elapsed since the instantaneous change in pumping rate.

If the rate of pumping is again increased, this time by ΔQ_2, and is maintained at the constant rate $(Q + \Delta Q_1 + \Delta Q_2)$, a third limb of the curve is obtained which follows the relationship:

$$Z = \frac{115Q}{T}\ W\left(\frac{1.87r^2S}{Tt}\right) + \frac{115\,\Delta Q_1}{T}\ W\left(\frac{1.87r^2S}{Tt'}\right) + \frac{115\,\Delta Q_2}{T}\ W\left(\frac{1.87r^2S}{Tt''}\right)$$

where t" is the time elapsed since the second change in pumping rate occurred.

Table 15. Determination of coefficient of transmissibility by modified Thiem method. Test on wells of group I, June 8 to July 11, 1938.

Well				10		11		12		14	
r				2,120		2,190		2,310		2,930	
$Log_{10}r$				3,326		3,340		3,364		3,467	
Date 1938	Hour	Q	ΔQ	z	Δz	z	Δz	z	Δz	z	Δz
June 8	8:00 a.m.										
		644									
June 20	8:00 a.m.		+130	61.13		61.49		57.77		46.77	
		744			+11.34		+11.59		+11.41		+8.73
June 30	11:00 a.m.		- 66	72.47		73.08		69.18		55.50	
		708			- 2.51		- 2.35		- 2.13		-0.17
July 11	1:22 p.m.			69.96		70.73		67.05		55.33	

Table 15a. Drawdowns measured at 8 a.m. June 20 and at 11 a.m. June 30.

Wells m	Wells n	$Log_{10} r_n/r_m$	$(\Delta z_n - \Delta z_m)$ ~~(feet)~~	Coefficient of transmissibility T
10	14	0.141	2.61	3,700
11	14	0.127	2.86	3,050
12	14	0.103	2.68	2,640
Average				3,130

Table 15b. Drawdowns measured at 11 a.m. June 30 and 1:22 p.m. July 11.

Wells m	Wells n	$Log_{10} r_n/r_m$	$(\Delta z_n - z_m \Delta)$	Coefficient of transmissibility T
10	14	0.141	2.34	2,100
11	14	0.127	2.18	2,020
12	14	0.103	1.96	1,830
Average				1,980

Average of the six computations - 2,560.

The base data obtained from the test of wells of group I are plotted in Figure 10. The numerical values taken from the curves are shown in tables 16a, b, c, d and e for the respective wells. The data for the second period of the test are plotted logarithmically in figure 10 and the usual procedure is followed in matching these curves to the type curve discussed on pp. 59 . Table 16 gives the coordinates of the points which represent the best fit of the several curves to the type curve, and the coefficients of transmissibility and storage are obtained therefrom.

The average of the coefficients of transmissibility derived from the second period of the test is 4,210, and the average of the coefficients of storage is 3.76×10^{-4}.

Table 16. Determination of coefficients of transmissibility and storage by modified graphical method. Second period of test on wells of group I, June 20 to 30, 1958

Well	Points representing best fit of curves to type curve r^2/t' $(x10^6)$	z'	u'	$W(u')$	Coefficient of transmissibility T	Coefficient of storage S
10	0.625	-9.2[illegible]	0.1	1.82	4,150	3.55×10^{-4}
11	0.660	-9.4[illegible]	0.1	1.82	4,060	3.29
12	0.660	-9.4[illegible]	0.1	1.82	4,060	3.29
13	1.68	-4.14	0.3	0.905	4,600	4.59
14	1.83	-3.99	0.35	0.793	4,180	4.27
Aver.					4,210	3.76×10^{-4}

Table 16a. Well 10, $r^2 = 4.49 \times 10^6$

Date 1938	Altitude of water level in feet, at 8 a.m., datum mean sea level	Δz	Time t' in days	$t'\Delta z$	Altitude of water level, in feet, from second limb of curve	Drawdown, $\Delta z'$, in feet	Time since change in rate of pumping, t', in days	r^2/t'
June 8	-51.45							
9	-53.56	-2.13	0.5	-1.07				
10	-55.25	-1.69	1.5	-2.54				
11	-56.57	-1.32	2.5	-3.30				
12	-57.57	-1.00	3.5	-3.50				
13	-58.37	-.80	4.5	-3.60				
14	-59.03	-.66	5.5	-3.63				
15	-59.60	-.57	6.5	-3.71				
16	-60.08	-.48	7.5	-3.60				
17	-60.48	-.40	8.5	-3.40				
18	-60.77	-.29	9.5	-2.75				
19	-60.97	-.20	10.5	-2.10				
20	-61.13	-.16	11.5	-1.84	-61.13	0	0	-
21	-61.27	-.14	12.5	-1.70	-63.07	1.80	1	4.49×10^6
22	-61.39	-.12	13.5	-1.57	-65.34	3.95	2	2.24
23	-61.49	-.10	14.5	-1.46	-67.03	5.54	3	1.496
24	-61.58	-.09	15.5	-1.35	-68.30	6.72	4	1.121
25	-61.66	-.08	16.5	-1.27	-69.35	7.69	5	0.897
26	-61.73	-.07	17.5	-1.20	-70.24	8.51	6	0.748
27	-61.79	-.06	18.5	-1.14	-70.93	9.14	7	0.641
28	-61.85	-.06	19.5	-1.08	-71.47	9.62	8	0.560
29	-61.90	-.05	20.5	-1.02	-71.97	10.07	9	0.499
30	-61.95	-.05	21.5	-0.98	-72.41	10.46	10	0.449

Table 16 b. Well 11, $r^2 = 4.80 \times 10^6$

Date 1938	Altitude of water level in feet, at 8 a.m., datum mean sea level	$-\Delta z$	Time t' in days	$-t'\Delta z$	Altitude of water level, in feet, from second limb of curve	Drawdown, -z', in feet	Time since change in rate of pumping, t', in days	r^2/t'
June 8	-51.40							
9	-53.58	2.18	0.5	1.09				
10	-55.31	1.73	1.5	2.60				
11	-56.67	1.36	2.5	3.40				
12	-57.74	1.07	3.5	3.75				
13	-58.60	0.86	4.5	3.87				
14	-59.31	0.71	5.5	3.91				
15	-59.84	0.53	6.5	3.45				
16	-60.32	0.48	7.5	3.60				
17	-60.73	0.41	8.5	3.49				
18	-61.05	0.32	9.5	3.04				
19	-61.30	0.25	10.5	2.63				
20	-61.49	0.19	11.5	2.19	-61.49	0	0	-
21	-61.64	0.15	12.5	1.92	-63.51	1.87	1	4.80×10^6
22	-61.77	0.13	13.5	1.74	-65.78	4.01	2	2.40
23	-61.88	0.11	14.5	1.60	-67.48	5.60	3	1.60
24	-61.98	0.10	15.5	1.49	-68.78	6.80	4	1.20
25	-62.07	0.09	16.5	1.40	-69.87	7.80	5	0.960
26	-62.15	0.08	17.5	1.32	-70.76	8.61	6	0.800
27	-62.22	0.07	18.5	1.25	-71.48	9.26	7	0.685
28	-62.28	0.06	19.5	1.19	-72.07	9.79	8	0.600
29	-62.34	0.06	20.5	1.14	-72.57	10.23	9	0.534
30	-62.39	0.05	21.5	1.09	-73.02	10.63	10	0.480

Table 16 c. Well 12, $r^2 = 5.34 \times 10^6$

Date 1938	Altitude of water level in feet, at 8 a.m., datum mean sea level	$-\Delta z$	Time t' in days	$-t'\Delta z$	Altitude of water level, in feet, from second limb of curve	Drawdown, $-z'$, in feet	Time since change in rate of pumping, t', in days	r^2/t'
June 8	-48.51							
9	-50.42	1.91	0.5	0.96				
10	-52.00	1.58	1.5	2.37				
11	-53.19	1.19	2.5	2.98				
12	-54.14	0.95	3.5	3.33				
13	-54.92	0.78	4.5	3.51				
14	-55.59	0.67	5.5	3.69				
15	-56.13	0.54	6.5	3.51				
16	-56.61	0.48	7.5	3.60				
17	-57.01	0.40	8.5	3.40				
18	-57.32	0.31	9.5	2.95				
19	-57.56	0.24	10.5	2.52				
20	-57.77	0.21	11.5	2.42	-57.77	0	0	-
21	-57.95	0.18	12.5	2.26	-59.53	1.58	1	5.34×10^6
22	-58.11	0.16	13.5	2.15	-61.79	3.68	2	2.67
23	-58.25	0.14	14.5	2.01	-63.53	5.28	3	1.780
24	-58.37	0.12	15.5	1.91	-64.91	6.54	4	1.335
25	-58.48	0.11	16.5	1.82	-66.00	7.52	5	1.069
26	-58.58	0.10	17.5	1.74	-66.91	8.33	6	0.890
27	-58.67	0.09	18.5	1.66	-67.63	8.96	7	0.763
28	-58.75	0.08	19.5	1.59	-68.23	9.48	8	0.668
29	-58.82	0.07	20.5	1.53	-68.72	9.90	9	0.594
30	-58.89	0.07	21.5	1.47	-69.12	10.23	10	0.534

Table 16 d. Well 13, $r^2 = 3.69 \times 10^6$

Date 1938	Altitude of water level in feet, at 8 a.m., datum mean sea level	$-\Delta z$	Time t' in days	$-t'\Delta z$	Altitude of water level, in feet, from second limb of curve	Drawdown, -z', in feet	Time since change in rate of pumping, t', in days	r^2/t'
June 8	-49.86							
9	-52.04	2.18	0.5	1.09				
10	-53.81	1.77	1.5	2.66				
11	-55.06	1.25	2.5	3.13				
12	-56.07	1.01	3.5	3.54				
13	-56.84	0.77	4.5	3.47				
14	-57.51	0.67	5.5	3.69				
15	-58.04	0.53	6.5	3.45				
16	-58.48	0.44	7.5	3.30				
17	-58.83	0.43	8.5	3.66				
18	-59.12	0.29	9.5	2.76				
19	-59.38	0.26	10.5	2.73				
20	-59.61	0.23	11.5	2.65	-59.61	0	0	-
21	-59.81	0.20	12.5	2.52	-61.67	1.86	1	3.69×10^6
22	-59.99	0.18	13.5	2.41	-63.60	3.61	2	1.845
23	-60.15	0.16	14.5	2.32	-65.48	5.33	3	1.230

Table 16 e. Well 14, $r^2 = 8.58 \times 10^6$

Date 1938	Altitude of water level in feet, at 8 a.m., datum mean sea level	$-\Delta z$	Time t' in days	$-t'\Delta z$	Altitude of water level, in feet, from second limb of curve	Drawdown, -z', in feet	Time since change in rate of pumping, t', in days	r^2/t'
June 8	-39.93							
9	-40.59	0.66	0.5	0.33				
10	-41.50	0.91	1.5	1.37				
11	-42.39	0.89	2.5	2.23				
12	-43.17	0.78	3.5	2.73				
13	-43.84	0.67	4.5	3.02				
14	-44.41	0.57	5.5	3.14				
15	-44.91	0.50	6.5	3.25				
16	-45.39	0.48	7.5	3.60				
17	-45.81	0.42	8.5	3.57				
18	-46.19	0.38	9.5	3.61				
19	-46.50	0.31	10.5	3.26				
20	-46.77	0.27	11.5	3.11	-46.77	0	0	-
21	-47.01	0.24	12.5	2.97	-47.45	0.44	1	8.58×10^6
22	-47.22	0.21	13.5	2.85	-48.64	1.42	2	4.29
23	-47.41	0.19	14.5	2.74	-49.86	2.45	3	2.86
24	-47.58	0.17	15.5	2.65	-51.00	3.42	4	2.145
25	-47.73	0.15	16.5	2.57	-52.01	4.28	5	1.716
26	-47.87	0.14	17.5	2.50	-52.92	5.05	6	1.430
27	-48.00	0.13	18.5	2.43	-53.70	5.70	7	1.226
28	-48.12	0.12	19.5	2.37	-54.39	6.27	8	1.072
29	-48.23	0.11	20.5	2.30	-54.95	6.72	9	0.953
30	-48.33	0.10	21.5	2.23	-55.44	7.11	10	0.858

Tables 17 a, b, c, and d give~~s~~ values of z" and $r^2/t"$ for wells 10, 11, 12, and 14 for the third period of the test. These data are plotted logarithmically in figure 17. From the best fit of the several curves to the type curve, the values of T and S as given in table 17, were computed. The value of ΔQ_2 used in making the computations is 774-700 = 74 gallons per minute. It is the difference between the average pumping rate during the third period and the effective average during the second period.

Because of the gradual increase in pumping rate during the third period of the test, the observed partial recovery continued to be less than it would have been had the pumping rate during that period been maintained at its initial value. Thus the corrected partial recovery curves shown in figure 17 have greater curvature than the type curve, the difference being even more pronounced than in figure 16.

Table 17. Determination of coefficients of transmissibility and storage by modified graphical method. Third period of test on wells of group I, June 30 to July 11, 1938

Well	r^2/t'' ($x10^6$)	Z''	U''	(u'')	Coefficient of transmissibility T	Coefficient of storage S
10	2.50	1.37	0.32	0.86	3,910	2.68×10^{-4}
11	4.33	1.12	0.55	0.50	3,800	2.58
12	0.90	3.68	0.115	1.69	3,910	2.67
14	0.958	2.72	0.155	1.43	4,470	3.87
Aver.					4,020	2.95×10^{-4}

Table 17 a. Well 10, $r^2 = 4.49 \times 10^6$

Date 1938	Altitude of water level in feet, at 8 a.m., datum mean sea level	$-\Delta z$	Time t' in days	$-t'\Delta z$		Altitude of water level, in feet, from third limb of curve	Recovery, z'', in feet	Time since change in rate of pumping, t'', in days	r^2/t''
June 20	-61.13								
21	-63.07	1.94	0.5	0.97					
22	-65.34	2.27	1.5	3.41					
23	-67.03	1.69	2.5	4.23					
24	-68.30	1.27	3.5	4.45					
25	-69.35	1.05	4.5	4.73					
26	-70.24	0.89	5.5	4.90					
27	-70.93	0.69	6.5	4.49					
28	-71.47	0.54	7.5	4.05					
29	-71.97	0.50	8.5	4.25					
30	-72.41	0.44	9.5	4.18	a)	-72.47	0	0	-
July 1	-72.78	0.37	10.5	3.88		-71.90	0.57	0.875	5.13×10^6
2	-73.11	0.33	11.5	3.76		-71.13	1.98	1.875	2.39
3	-73.40	0.29	12.5	3.65		-70.57	2.83	2.875	1.56
4	-73.66	0.26	13.5	3.56		-70.18	3.48	3.875	1.16
5	-73.90	0.24	14.5	3.48		-70.01	3.89	4.875	0.920
6	-74.12	0.22	15.5	3.40		-69.94	4.18	5.875	0.764
7	-74.32	0.20	16.5	3.34		-69.92	4.40	6.875	0.652
8	-74.51	0.19	17.5	3.28		-69.93	4.58	7.875	0.570
9	-74.68	0.17	18.5	3.20		-69.94	4.74	8.875	0.505
10	-74.84	0.16	19.5	3.14		-69.95	4.89	9.875	0.455
11	-74.99	0.15	20.5	3.08		-69.96	5.03	10.875	0.413

a) at 11 a.m.

Well 11, r^2 = 4.80 x 10^6

Table 17 b.

Date 1938	Altitude of water level in feet, at 8 a.m., datum mean sea level	$-\Delta z$	Time t' in days	$-t'\Delta z$	Altitude of water level, in feet, from third limb of curve	Recovery, z", in feet	Time since change in rate of pumping, t", in days	$r^2/t"$
June 20	-61.49							
21	-63.51	2.02	0.5	1.01				
22	-65.78	2.27	1.5	3.41				
23	-67.48	1.70	2.5	4.25				
24	-68.78	1.30	3.5	4.55				
25	-69.87	1.09	4.5	4.91				
26	-70.76	0.89	5.5	4.90				
27	-71.48	0.72	6.5	4.68				
28	-72.07	0.59	7.5	4.43				
29	-72.57	0.50	8.5	4.25				
30	-73.02	0.45	9.5	4.28	-73.08	0	0	-
July 1	-73.40	0.38	10.5	3.98	-72.55	0.85	0.875	5.49 x 10^6
2	-73.74	0.34	11.5	3.87	-71.79	1.95	1.875	2.56
3	-74.04	0.30	12.5	3.78	-71.25	2.79	2.875	1.670
4	-74.31	0.27	13.5	3.69	-70.92	3.39	3.875	1.240
5	-74.56	0.25	14.5	3.61	-70.74	3.82	4.875	0.985
6	-74.79	0.23	15.5	3.53	-70.70	4.09	5.875	0.816
7	-75.00	0.21	16.5	3.47	-70.71	4.29	6.875	0.699
8	-75.19	0.19	17.5	3.39	-70.72	4.47	7.875	0.610
9	-75.37	0.18	18.5	3.32	-70.72	4.65	8.875	0.541
10	-75.54	0.17	19.5	3.26	-70.73	4.81	9.875	0.486
11	-75.70	0.16	20.5	3.20	-70.73	4.97	10.875	0.441

a) at 11 a.m.

Well 17 c.

Well 12, $r^2 = 5.34 \times 10^6$

Date 1938	Altitude of water level in feet, at 8 a.m., datum mean sea level	$-\Delta z$	Time t', in days	$-t'\Delta z$	Altitude of water level, in feet, from third limb of curve	Recovery, z'', in feet	Time since change in rate of pumping, t'', in days	r^2/t''
June 20	-57.77							
21	-59.53	1.76	0.5	0.88				
22	-61.79	2.26	1.5	3.39				
23	-63.53	1.74	2.5	4.35				
24	-64.91	1.38	3.5	4.83				
25	-66.00	1.09	4.5	4.91				
26	-66.91	0.91	5.5	5.01				
27	-67.63	0.72	6.5	4.68				
28	-68.23	0.60	7.5	4.50				
29	-68.72	0.49	8.5	4.12				
30	-69.12	0.40	9.5	3.80	a) -69.18	0	0	-
July 1	-69.47	0.35	10.5	3.67	-68.79	0.68	0.875	6.10×10^6
2	-69.78	0.31	11.5	3.61	-68.12	1.66	1.875	2.84
3	-70.05	0.27	12.5	3.38	-67.61	2.44	2.875	1.855
4	-70.29	0.24	13.5	3.27	-67.28	3.01	3.875	1.377
5	-70.51	0.22	14.5	3.18	-67.12	3.39	4.875	1.094
6	-70.71	0.20	15.5	3.10	-67.06	3.65	5.875	0.909
7	-70.89	0.18	16.5	3.03	-67.03	3.86	6.875	0.776
8	-71.06	0.17	17.5	2.98	-67.04	4.02	7.875	0.678
9	-71.22	0.16	18.5	2.92	-67.05	4.17	8.875	0.601
10	-71.37	0.15	19.5	2.87	-67.05	4.32	9.875	0.540
11	-71.51	0.14	20.5	2.81	-67.05	4.46	10.875	0.490

a) at 11 a.m.

Table 17 d. Well 14, $r^2 = 8.58 \times 10^6$

Date 1938	Altitude of water level in feet, at 8 a.m., datum mean sea level	$-\Delta z$	Time t' in days	$-t'\Delta z$		Altitude of water level, in feet, from third limb of curve	Recovery z'', in feet	Time since change in rate of pumping, t'', in days	r^2/t''
June 20	-46.77								
21	-47.45	0.68	0.5	0.34					
22	-48.64	1.19	1.5	1.79					
23	-49.86	1.22	2.5	3.05					
24	-51.00	1.14	3.5	3.99					
25	-52.01	1.01	4.5	4.55					
26	-52.92	0.91	5.5	5.01					
27	-53.70	0.78	6.5	5.07					
28	-54.39	0.69	7.5	5.18					
29	-54.95	0.56	8.5	4.76					
30	-55.44	0.49	9.5	4.66	a)	-55.50	0	0	-
July 1	-55.86	0.42	10.5	4.40		-55.82	0.04	0.875	9.80×10^6
2	-56.23	0.37	11.5	4.25		-55.80	0.43	1.875	4.57
3	-56.56	0.33	12.5	4.12		-55.60	0.96	2.875	2.98
4	-56.86	0.30	13.5	4.00		-55.45	1.41	3.875	2.21
5	-57.13	0.27	14.5	3.92		-55.34	1.79	4.875	1.760
6	-57.38	0.25	15.5	3.83		-55.27	2.11	5.875	1.460
7	-57.61	0.23	16.5	3.78		-55.23	2.38	6.875	1.248
8	-57.82	0.21	17.5	3.74		-55.28	2.54	7.875	1.089
9	-58.02	0.20	18.5	3.68		-55.30	2.72	8.875	0.967
10	-58.21	0.19	19.5	3.63		-55.31	2.90	9.875	0.869
11	-58.39	0.18	20.5	3.59		-55.33	3.06	10.875	0.790

a) at 11 a.m.

Determination of coefficient of storage by measurement of maximum change in rate of decline or recovery of water levels.

The equation developed by Theis giving the drawdown at any point and at any time around a well that is pumped at a uniform rate from a homogeneous aquifer of constant thickness and infinite areal extent, affords a basis for the determination of the coefficient of transmissibility by measurement of the maximum change in the rate of decline or recovery of water levels. The equation is as follows: $Z = \frac{114.60}{T}\int_{u}^{\infty} \left(\frac{e^{-u}}{u} \right) du$ where the symbols have the same meaning as previously.

It can be shown that as a consequence of this relationship, the following equation holds, provided there is an instantaneous change (ΔQ) in the rate of pumping: $S = \frac{22.5\Delta Q}{r^2 \Delta (\frac{\partial z}{\partial t})_{max.}}$, where $\frac{\partial Z}{\partial t}$ is measured in feet a day, and where Q is in gallons a minute, as before.

Table 18 gives values of the coefficient of storage determined in this manner from the maximum change in the rate of decline of water levels during the second period of the test on wells of group I. The maximum change in rate of decline is taken as the difference between the maximum slope of the second limb of a particular drawdown curve and the slope of the extrapolated portion of the first limb of the same curve. The latter is given in the fourth column of the table headed "correction (ft/day)". Table 19 gives values for the coefficient of storage that are similarly computed from the maximum rate of recovery of water levels during the third period of the test of wells of group I.

As the maximum change in rate of decline or recovery in four of the five observation wells occurred within about a day of the time when the change in the rate of pumping occurred, the change in pumping rate (ΔQ) was taken as the difference between the average pumpage rate during the first day of the given period and the effective average for the preceding period.

Table 18. Determination of coefficient of storage from maximum change in rate of decline of water levels during second period of tests on wells of group I.

Well	r	Maximum slope of second limb of curve (ft/day)	Correction (ft/day)	Maximum change in rate of decline (ft/day)	Coefficient of storage S
10	4.49×10^{6}	-2.58	-0.14	2.44	5.44×10^{-4}
11	4.80	-2.64	-0.15	2.49	4.98
12	5.34	-2.41	-0.18	2.23	5.00
13	3.69	-2.46	-0.20	2.26	7.14
14	8.58	-1.25	-0.24	1.01	6.86
Aver.					5.88×10^{-4}

Table 19. Determination of coefficient of storage from maximum change in rate of recovery of water levels during third period of test on wells of group I.

Well	r	Maximum slope of third limb of curve (ft/day)	Correction (ft/day)	Maximum change in rate of decline (ft/day)	Coefficient of storage S
10	4.49×10^{6}	0.96	-0.37	1.33	4.20×10^{-4}
11	4.80	0.88	-0.38	1.26	4.15
12	5.34	0.72	-0.35	1.07	4.40
13	3.69	-	-	-	-
14	8.58	0.28	-0.42	0.70	4.19
Aver.					4.24×10^{-4}

Accordingly the values of ΔQ are as follows:

For the second period:

$$\Delta Q = (907-644) = 263.$$

For the third period:

$$\Delta Q = (774-663) = 111.$$

The average value of the coefficient of storage as determined from the computations based on the pumping of the wells of group I is 5.88×10^{-4} for the second period and 4.24×10^{-4} for the third period.

Summary of determinations of coefficients of transmissibility and storage.

The following table summarizes the determinations of coefficients of transmissibility and storage resulting from the application of the various methods. The significance of the coefficients as determined by the different methods is discussed on pages 39-42.

Table 9 Summary of determinations of coefficients of transmissibility and storage by various methods.

Pumping test on:	Method	Period of test	Coefficient of transmissibility T	Coefficient of storage S
Well 11	Thiem		2,310	---
	Theis recovery		1,770	---
	Graphical		2,590	4.42×10^{-4}
Group I	Thiem	II	1,130	---
		III	1,980	---
	Graphical	II	4,210	3.76×10^{-4}
		III	4,020	2.95×10^{-4}
	Maximum slope	II	---	5.88×10^{-4}
		III	---	4.24×10^{-4}