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DISCHARGE FROM A SANDPOINT WELL SYSTEM FOR A THIN AQUIFER IN THE SIOUX RIVER AREA

By

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This thesis is approved as a creditable, independent investigation by a candidate for the degree, Master of Science, and acceptable as meeting the thesis requirements for this degree; but without implying that the conclusions reached by the candidate are necessarily the conclusions of the major department.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

One of the principal sources of water for irrigation is the underground water stored beneath the surface of the earth. Various methods have been devised to extract this water so that it may be applied to growing crops in regions of inadequate rainfall.

Near the Sioux River in Eastern South Dakota, ample water has been obtained at shallow depths to irrigate average sized fields in certain areas. A sandpoint well system, which consists of four or five sandpoints connected to a centrifugal pumping unit, is being used to remove the water from the ground and force it through a sprinkler irrigation system. Many problems have been encountered in the application of such a system and several of them remain unsolved. One of the more important considerations involves the optimum spacing of the sandpoints to obtain the greatest discharge. Other problems such as a convenient means of priming the pump, methods of installing the sandpoints, and the value of gravel packing the wells also need attention. It is the purpose of this study to determine the effect of the sandpoint spacing on the quantity of water secured from a sandpoint well system by obtaining the discharge for various spacings of from one to five sandpoints connected in series. In order to present the material necessary for the solution of this problem, it is expedient to introduce some concepts involving ground water hydrology.

Underground water is found between the aggregates and the rocks which usually occur in well-defined layers varying greatly in thickness. Such a formation or layer of permeable materials capable of yielding appreciable quantities of gravity ground-water when saturated is known as an aquifer.

An aquifer may be located just a few feet below the topsoil, or it may occur at great depths and be confined under pressure by another layer of impervious material that prevents the water from escaping. This confining layer is known as an aquiclude and creates an artesian condition.

A more familiar condition is the non-artesian or unconfined aquifer which has a free water surface known as the water table. Below the water table is the zone of saturation where the aquifer has the ability to transmit a certain quantity of water under an existing hydraulic gradient. A hydraulic gradient is represented by the elevation to which the water rises at successive locations along a line of flow.

> The term coefficient of transmissibility introduced by Theis is coming into popular usage in ground-water hydrology. The coefficient of transmissibility is defined as the rate of flow of water in gallons per day through a vertical strip of the aquifer 1 ft wide and extending the full saturated height under a hydraulic gradient of 100 per cent at a temperature of 60° F.[1]

The coefficient of transmissibility is related to another term known as the coefficient of permeability. This coefficient multiplied by the thickness of the aquifer equals the coefficient of transmissibility.

The water table has several peculiarities. It may be entirely level where there is no underground flow, or it may slope considerably due to a hydraulic gradient when there is lateral movement of water in the ground. Changes in barometric pressure can cause vertical fluctuation of the water table elevation, especially under artesian conditions. If the water table is near the surface of the ground, it will fluctuate during the day because

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[1] Wisler, C. O., Brater, E. F. Hydrology. New York, John Wiley & Sons, Inc. 1949. p. 206.

of water that is removed by superficial evaporation and plant transpiration. Over a long period of time the water table will gain or lose some elevation due to regional change. This fluctuation may occur from replenishment by rainfall and melting snow, or it may represent a gradual decline due to transpiration, evaporation, or outflow from the aquifer.

When an aquifer is penetrated by a well and water is removed by pumping, the deprivational effect on the water table will be noticed first in the immediate area of the well. As the amount and duration of pumping is increased, the areal extent of influence on the water table becomes greatly widened. C. V. Theis, well known for his contributions to the study of ground water, describes the nature of the cone of depression in the following statements.

> The term cone of depression . . . denotes the geometric solid included between the water table or other piezometric surface after a well has begun discharging and the hypothetical position the water table or other piezometric surface would have had if there had been no discharge by the well . . . . The vertical distance at any place between the hypothetical uninfluenced position of the piezometric surface and the actual surface after discharge has begun, that is, the lowering due to the discharge, is the drawdown at that place caused by the discharge.[2]

Where the water table is within a few feet of the surface of the ground, water may be removed by a shallow well pump. One type of well adapted to these conditions is the sandpoint well. The sandpoint consists of a piece of pipe with screen-like openings in the sides to allow the water to enter. One end is threaded to couple to an ordinary well pipe and the other end is made of a short, solid, conical point. The sandpoint is

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[2] Theis, C. V. The significance and nature of the cone of depression in ground-water bodies. (Abstract) Economic Geology. 33, no. 8: 889-902. 1938.

coupled to the desired length of well pipe and driven into the water-bearing aquifer. Several of these sandpoint wells are connected to one suction pump by horizontal pipe to form a sandpoint well system.

The quantity of discharge that may be expected from such a well system is determined by the combined effects of several conditions. The coefficient of transmissibility of the aquifer is the natural characteristic upon which the yield of the aquifer is dependent. Closely related to this is the efficiency of the well itself. If the sandpoint is driven so that the screen becomes located in fine textured material that transmits water very slowly, a low well efficiency can be expected. However, if the screen is located in some material of similar texture to that indicated by the average coefficient of transmissibility for the entire aquifer, the flow into the well will be restricted very little.

The quantity of discharge is directly related to the drawdown in the well and the surrounding aquifer. The drawdown is equal to the vertical effects of pumping at a certain point. This drawdown is dependent upon and restricted by the maximum suction lift of the pumping unit which can only be as great as the vacuum that the pump is able to create. An absolute vacuum is equal to a pressure of 14.7 lbs. per sq. in. at sea level or a pressure that will support a head of water 33.9 feet high. At the altitude of Eastern South Dakota a vacuum is reduced to approximately 32 feet of water pressure. However, an absolute vacuum has never been obtained and this limitation is further restricted by the efficiency of the pumping unit itself. For a centrifugal pump the maximum suction lift is generally considered to be 15 feet because pump efficiency drops rapidly with a greater lift.

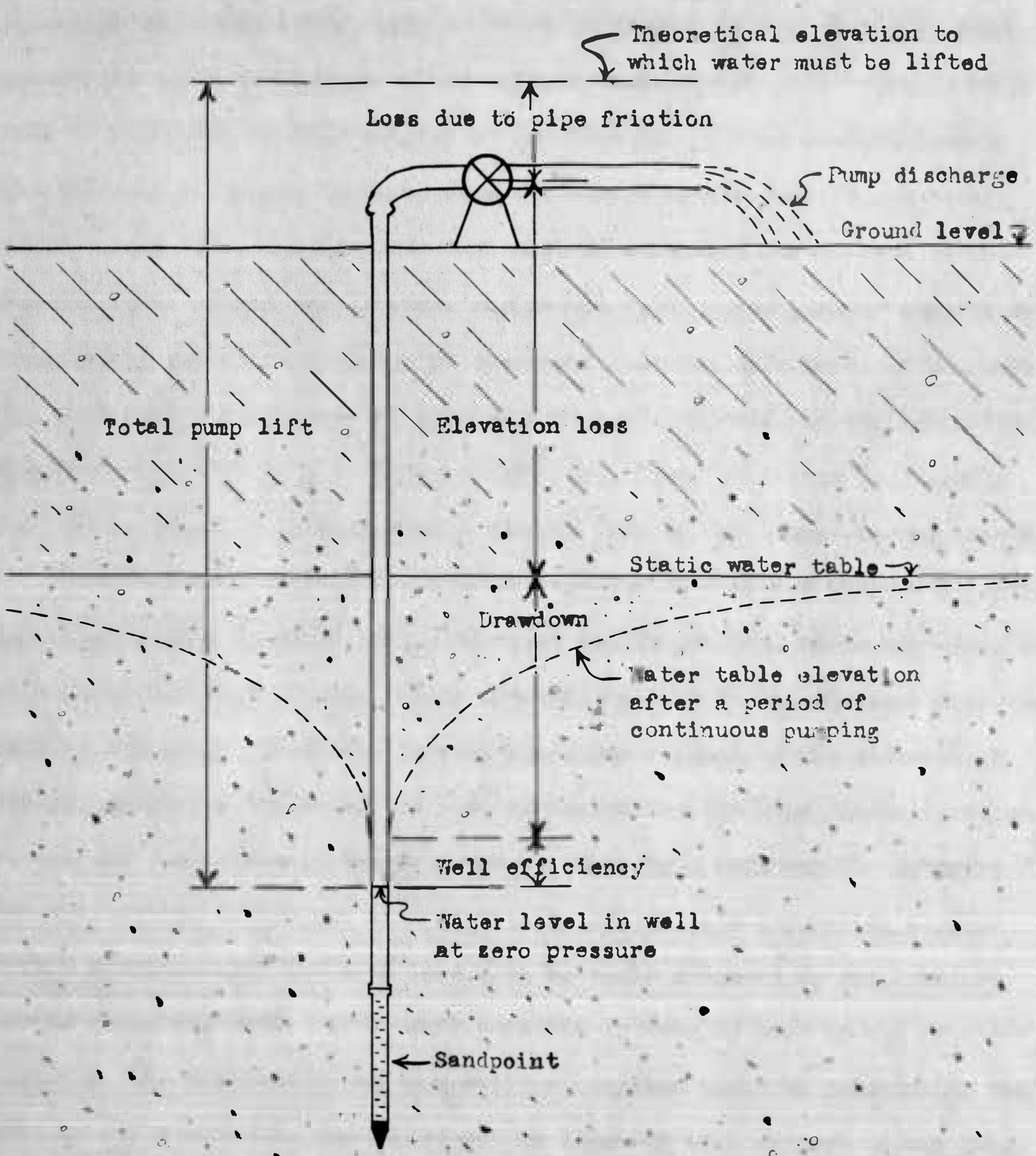

Figure 1. The Components That Constitute Total Pump Lift in Pumping a Sandpoint Well

A typical illustration of the losses that occur by pumping a sandpoint connected to a centrifugal pump is shown in Figure 1. For instance, when pumping 80 to 90 gallons per minute with a maximum lift of 15 feet, 2 to 3 feet of head will be lost because of friction in a 2 inch sandpoint well. The vertical distance, in feet, from the center of the pump to the water table represents elevation loss that must be accounted for as part of the suction lift. Also, the drawdown inside the well may be greater than it is immediately outside the well pipe depending upon the efficiency of the well. The remainder, after these losses are accounted for, will be available for drawdown at the well to determine discharge. Since discharge is directly related to drawdown, the discharge becomes less as the losses become greater.

Where several wells are connected together in a system (Figure 2), head loss due to pipe friction is an important consideration. Since head loss is calculated per foot of pipe, it is directly related to the distance from the well to the pump. Head loss is also inversely related to the diameter of the pipe carrying the water, so that by increasing the pipe diameter, it can be reduced for a certain length of pipe. This loss will rapidly decrease drawdown unless it is kept to a minimum by selecting a connecting pipe of such a diameter that the head loss will be small compared to the drawdown in the sandpoint well. If it were possible to have no loss in the connecting pipe, the drawdown in any one well in a system would be practically the same as any other well regardless of its location with respect to the pump. Therefore, if the pipe friction is made negligible, as distance between the wells is increased, overlapping of the cones of depression becomes less, and the total discharge of the system increases. It is evident that the discharge will be influenced by well spacing, but the effect is not as great

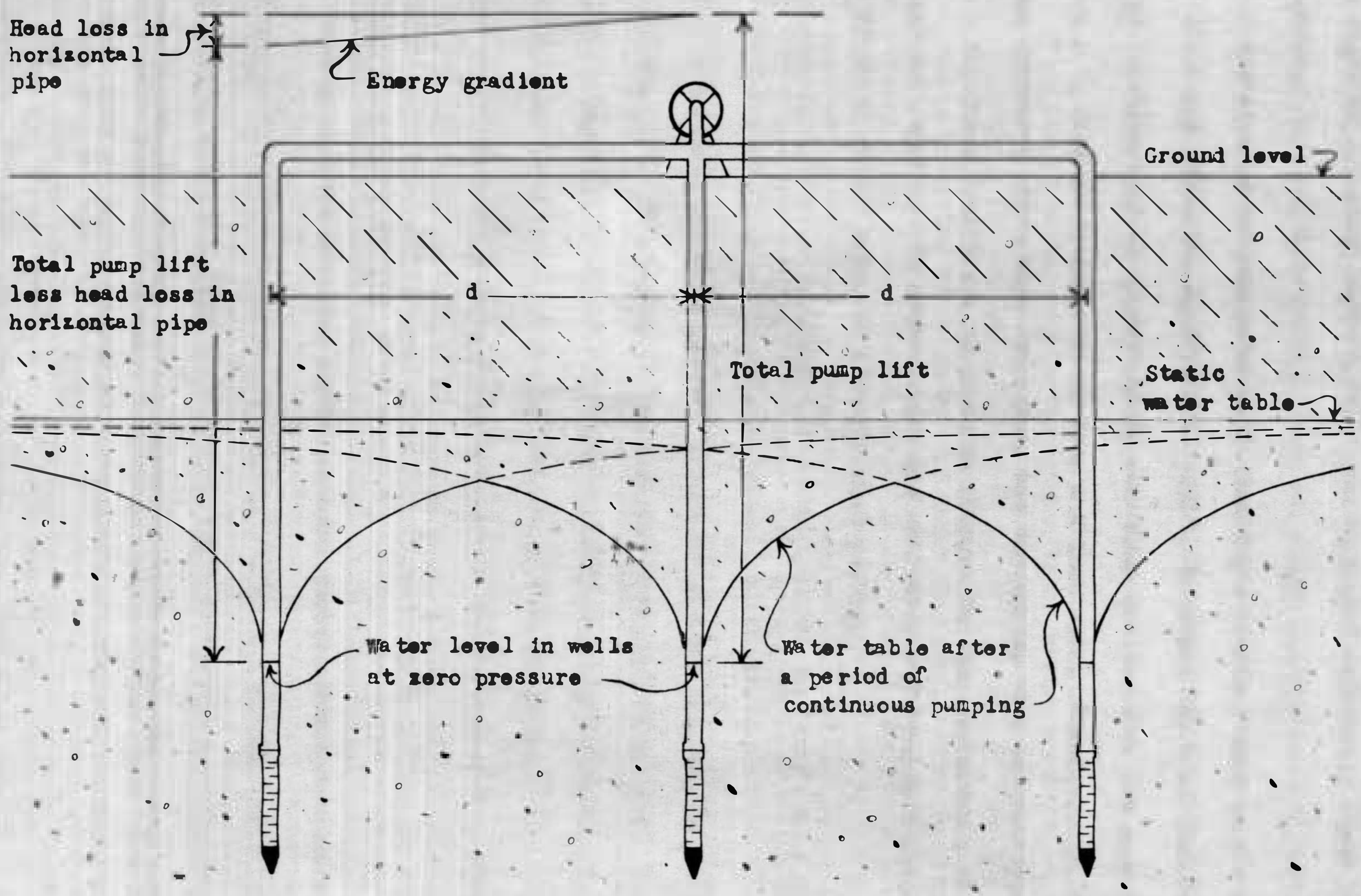

Figure 2. Existing Conditions for a Sandpoint Well System Consisting of Three Wells

as might be expected, and the wells can be placed relatively close to one another.

The size of the sandpoint well itself has little effect on the quantity of discharge which the aquifer will yield. However, the head loss due to pipe friction will be approximately ten times greater with the same discharge from a $1\frac{1}{4}$ inch sandpoint well as from a 2 inch well. Consequently, the maximum drawdown, which also determines the discharge, will be greatly reduced.

All these conditions interact to account for the performance of a sandpoint well system. To separate any one condition and determine its effect or limiting factor presents a complicated problem.

WORK OF OTHER INVESTIGATORS

Perhaps more work has been done on ground water studies by members of the United States Geological Survey than any other organization or individual. R. H. Brown, Hydraulic Engineer, Ground Water Division, U. S. Geological Survey, has made a general statement as follows:

> As is well known, studies of ground water resources are continually being made by the Ground Water Branch of the U. S. Geological Survey in cooperation with many state and local agencies throughout the country. This work is directed toward locating ground water reservoirs and learning as much as possible about them, including their extent and their ability to store and transmit water. Examination and comparison of the methods used in making these studies would reveal no completely stereotyped pattern of procedure. In fact, each study would appear to involve its own peculiar combination of geologic and hydrologic factors requiring individual methods of analysis. Over the years, therefore, the USGS has developed quite a large store of qualitative and quantitative geologic and hydrologic methods of study.[3]

Brown has presented a direct procedure of applying the Theis nonequilibrium formula to drawdown data obtained from two observation wells located near a pumped well. The result is a coefficient of transmissibility and a coefficient of storage for the aquifer he was working with. He states: "The coefficient of storage is defined as the relative amount of water released from storage in a unit vertical prism of the aquifer as the piezometric head declines 1 ft."[4]

In a chapter on ground water[5] by J. G. Ferris, District Engineer, Ground Water Division, U. S. Geological Survey, the nature of underground

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[3] Brown, Russell H. Selected procedures for analyzing aquifer test data. (Reprint) Journal of American Water Works Association. 45: 844. 1953.

[4] Ibid., p. 848.

[5] Ferris, J. G. Ground Water. In Wisler, C. O., Brater, E. F. Hydrology. New York, Johy Wiley & Sons, Inc. 1949. p. 198-272.

storage and flow, particularly with respect to an artesian aquifer, are discussed. He describes several methods for determining the coefficient of permeability of unconsolidated materials. His discussion on ground water hydraulics deals in detail with the derivation of the formulas for finding the coefficient of transmissibility and the coefficient of storage for an aquifer. Before deriving the nonequilibrium formula, he credits C. V. Theis in the following statement: "A major advancement in ground water hydraulics was made by Theis in 1935 with his development of the nonequilibrium formula which introduces the time factor and the specific yield or coefficient of storage."[6] Ferris also describes the method of images as a tool for locating recharge and impervious boundaries in an aquifer.

In Water Supply Paper 887 L, K. Wenzel, U. S. Geological Survey, deals with methods for determining the permeability of water-bearing materials. He explains the procedure for determining permeability by discharging-well methods and describes some of the pump tests made in Kansas and Nebraska by the Geological Survey. Tests were conducted near Grand Island, Kearney, Gothenburg, and Scottsbluff, Nebraska, and Wichita, Kansas.

As a result of these tests, Wenzel states the effectiveness of the wells was found to range from 41% for the Grand Island well to 120% for the Gothenburg well. The ineffectiveness of the Grand Island well was obvious because the water level just outside the well was observed to

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[6] Ibid., p. 231.

stand about 10 feet higher than the water level inside the well casing while pumping was in progress. The low effectiveness of the Grand Island and the Scottsbluff wells was attributed to the fact that these two wells did not penetrate the entire thickness of the water-bearing material. The other three wells, which were more highly effective, completely penetrated the water-bearing materials. The effectiveness of over 100% in the Gothenburg well is explained in the following statement:

> An effectiveness of 100 percent indicates that the well casing and material around the well function as if there were no loss of head caused by the entrance of the water into the well. Where the well has been considerably developed the effective radius of the well is increased and the apparent effectiveness of the well under such conditions may be much greater than for perfect conditions with a smaller effective radius. By well development the permeability of the water-bearing material around the well may be considerably increased over that of the rest of the formation, and while the well is being pumped the slope of the water level through the material with the increased permeability may be considerably less than the slope that would have prevailed had the well been undeveloped. The drawdown in the pumped well will be decreased proportionally by the well development. It is thus possible to construct a well that for the diameter of its casing is more than 100 percent effective.[7]

The specific capacities of these wells (discharge per foot of drawdown) ranged from 27 to 100 gallons per minute for the Grand Island and the Kearney wells, respectively. The other specific capacities were 51.7, 55.2, and 66.7 for the Gothenburg, Scottsbluff, and Wichita wells, in the respective order as stated.

The Johnson Well Company of St. Paul, Minnesota, has had practical experience with wells including sandpoint well systems. They use such systems to obtain water for irrigation as well as for municipal or industrial

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[7] Wenzel, L. K. Methods for determining permeability of water-bearing materials. U. S. Geological Survey Water-Supply Paper 887. 1942. p. 150.

purposes, to temporarily dewater construction sites in wet ground, and to permanently lower the water table over an area for special reasons.

An interesting article appears in The Johnson National Drillers Journal on well-point systems explaining the conditions associated with their use. From their experience, they recommend spacings of 25 to 50 feet between wells in a water supply system. Closer spacing was recommended in fine sand formations and thin aquifers when the maximum drawdown may not exceed 5 feet. They make the following statement concerning piping and connections:

> The important point in choosing pipe sizes for the riser pipe or well casing and the suction header is to make them generously large. By using piping as large as practicable, friction losses in the system are kept to a minimum. This makes more of the total suction head of the pump available to produce drawdown in the wells. The net effect is to increase the yield of the system almost in direct proportion. For example, if the drawdown in the wells can be increased from 9 feet to 10 feet the yield will go up about 10 per cent.[8]

Interest has been shown recently in adapting these well-point systems to supplying water for sprinkler irrigation systems. The major problem seems to be the inconsistency in the general performance of such a pumping system due to the many hydrologic conditions that may affect it.

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[8] Well-point systems for supply and dewatering. The Johnson National Drillers Journal. 26, no. 5: 6. Sept.-Oct. 1954.

ANALYSIS OF THE PROBLEM

The most desirable spacing of the sandpoints in a well system is the minimum interval that will allow the system to provide the quantity of discharge required to satisfy the duty of the water. When this spacing is exceeded, unnecessary pipe is required to join the sandpoints to the pump thereby increasing the cost of the system. Consequently, in order to obtain the most satisfactory spacing of the sandpoints, it is essential to know the amount of discharge that can be expected of the system that is being installed. By the use of the coefficient of transmissibility determined for the aquifer in question, it is possible to calculate the discharge from a sandpoint well system with Theis' nonequilibrium formula.

The coefficient of transmissibility for the strata where the sandpoint is installed is found by applying the nonequilibrium formula to the data obtained by performing an actual pump test on the aquifer. While the test well is being pumped, periodic measurements of water table drawdown are taken in observation wells located near the pumped well throughout the duration of the test.

Before the pump test is conducted, preliminary investigation is necessary to determine the daily variations that occur due to barometric pressure and regional change. This investigation is important in order to find the magnitude of the water table fluctuation caused by these factors. Where this fluctuation is minor compared with the accuracy of the measurements taken during the pump test, it becomes relatively insignificant in the analysis of the data.

In the Sioux River aquifer water table measurements were taken simultaneously with readings from a barometer located about 6 miles away at South

Dakota State College. A depression of the water table in an observation well was found to coincide with an increase in the barometric reading. Likewise, a falling barometer reading accompanied a rising water level in the observation well. After carefully studying the degree of influence of the barometric pressure over a period of several weeks, the magnitude of the water table fluctuation for ordinary daily air pressure variation was found to range from approximately 0.01 to 0.001 foot. Thus, when compared to a precision of 0.01 foot in measurements to be taken during a pump test, it was concluded the effect of barometric pressure could be neglected.

During the period of water table study for barometric effects, the influence of regional change was also noted. This change appeared as a general trend in the form of a very slowly rising or falling water table depending upon the natural replenishment or depletion of the underground water supply. The magnitude of this change was found to be 0.005 foot or less per day. It was further discovered that during the period of the pump test used for the data in this thesis the regional change was undergoing a transition from falling to rising. It was assumed the water table was very stable during that period as far as the effect of regional change was concerned and that this effect could very well be neglected during the pump test.

The elimination of the effects of these external factors simplified the analysis of the data. However, since the aquifer tested was relatively thin compared to the total drawdown after pumping, a correction for this condition was made on the observed drawdown. This correction factor which must be subtracted from the observed drawdown is equal to $(s_1)^2/2m$ where s_1 is observed drawdown and m is the thickness of the aquifer.

The nonequilibrium formula used for analyzing the corrected pump test data follows:

$$s=(114.6\ Q/T)\ W(u)$$

where s=corrected drawdown in feet
Q=discharge in gallons per minute
T=coefficient of transmissibility in gallons per day per foot
$W(u)$= "well function of u", an exponential integral

$$\text{and } W(u)=\int_{1.87\ r^2S/Tt}^{\infty}\frac{e^{-u}}{u}du=-0.577216-\log_e u+u-\frac{u^2}{2.2!}+\frac{u^3}{3.3!}\ \cdots$$

Therefore $u=1.87\ r^2S/Tt$ or $r^2/t=(T/1.87S)\ u$

where S=coefficient of storage
r=distance from the pumped well to the observation well in feet
t=time since pumping started in days

The actual values of W(u) for values of u in the above integral ranging from $1\text{x}10^{-15}$ to 9.9 have been calculated and tabulated by the U. S. Geological Survey (Table 1). By plotting these values against each other on logarithmic coordinate tracing paper, a type curve is developed which represents the change in W(u) corresponding to a similar change in u. A segment of this curve is shown in Figure 3.

The pump test data are plotted on logarithmic paper by plotting s against r^2/t to the same scale as the type curve. Considering Q, S, and T as constants during a pump test, it is evident in the above equations that s is related to r^2/t in a manner similar to the relation of W(u) to u. Consequently, when plotted to the same scale, the pump test data will produce a curve similar to the type curve shown in Figure 3. By holding the coordinate axes of the type curve parallel to the axes of the plotted data for the wells and selecting their best match position, the type curve is superimposed on the field data. When any point is chosen on the fitted curve, the respective

Table 1. Values of W(u) for Nonequilibrium Formula[*]

N \ u	$N \times 10^{-15}$	$N \times 10^{-14}$	$N \times 10^{-13}$	$N \times 10^{-12}$	$N \times 10^{-11}$	$N \times 10^{-10}$	$N \times 10^{-9}$	$N \times 10^{-8}$	$N \times 10^{-7}$	$N \times 10^{-6}$	$N \times 10^{-5}$	$N \times 10^{-4}$	$N \times 10^{-3}$	$N \times 10^{-2}$	$N \times 10^{-1}$	N
1.0	33.9616	31.6590	29.3564	27.0538	24.7512	22.4486	20.1460	17.8435	15.5409	13.2383	10.9357	8.6332	6.3315	4.0379	1.8229	0.2194
1.1	33.8662	31.5637	29.2611	26.9585	24.6559	22.3533	20.0507	17.7482	15.4456	13.1430	10.8404	8.5379	6.2363	3.9436	1.7371	.1860
1.2	33.7792	31.4767	29.1741	26.8716	24.5689	22.2663	19.9637	17.6611	15.3586	13.0560	10.7534	8.4509	6.1494	3.8576	1.6595	.1584
1.3	33.6992	31.3966	29.0940	26.7914	24.4889	22.1863	19.8837	17.5811	15.2785	12.9759	10.6734	8.3709	6.0695	3.7785	1.5889	.1355
1.4	33.6251	31.3225	29.0199	26.7173	24.4147	22.1122	19.8096	17.5070	15.2044	12.9018	10.5993	8.2968	5.9955	3.7054	1.5241	.1162
1.5	33.5561	31.2535	28.9509	26.6483	24.3458	22.0432	19.7406	17.4380	15.1354	12.8328	10.5303	8.2278	5.9266	3.6374	1.4645	.1000
1.6	33.4916	31.1890	28.8864	26.5838	24.2812	21.9786	19.6760	17.3735	15.0709	12.7683	10.4657	8.1634	5.8621	3.5739	1.4092	.08631
1.7	33.4309	31.1283	28.8258	26.5232	24.2206	21.9180	19.6154	17.3128	15.0103	12.7077	10.4051	8.1027	5.8016	3.5143	1.3578	.07465
1.8	33.3738	31.0712	28.7686	26.4660	24.1634	21.8608	19.5583	17.2557	14.9531	12.6505	10.3479	8.0455	5.7446	3.4581	1.3098	.06471
1.9	33.3197	31.0171	28.7145	26.4119	24.1094	21.8068	19.5042	17.2016	14.8990	12.5964	10.2939	7.9915	5.6906	3.4050	1.2649	.05620
2.0	33.2684	30.9658	28.6632	26.3607	24.0581	21.7555	19.4529	17.1503	14.8477	12.5451	10.2426	7.9402	5.6394	3.3547	1.2227	.04890
2.1	33.2196	30.9170	28.6145	26.3119	24.0093	21.7067	19.4041	17.1015	14.7989	12.4964	10.1938	7.8914	5.5907	3.3069	1.1829	.04261
2.2	33.1731	30.8705	28.5679	26.2653	23.9628	21.6602	19.3576	17.0550	14.7524	12.4498	10.1473	7.8449	5.5443	3.2614	1.1454	.03719
2.3	33.1286	30.8261	28.5235	26.2209	23.9183	21.6157	19.3131	17.0106	14.7080	12.4054	10.1028	7.8004	5.4999	3.2179	1.1099	.03250
2.4	33.0861	30.7835	28.4809	26.1783	23.8758	21.5732	19.2706	16.9680	14.6654	12.3628	10.0603	7.7579	5.4575	3.1763	1.0762	.02844
2.5	33.0453	30.7427	28.4401	26.1375	23.8349	21.5323	19.2298	16.9272	14.6246	12.3220	10.0194	7.7172	5.4167	3.1365	1.0443	.02491
2.6	33.0060	30.7035	28.4009	26.0983	23.7957	21.4931	19.1905	16.8880	14.5854	12.2828	9.9802	7.6779	5.3776	3.0983	1.0139	.02185
2.7	32.9683	30.6657	28.3631	26.0606	23.7580	21.4554	19.1528	16.8502	14.5476	12.2450	9.9425	7.6401	5.3400	3.0615	.9849	.01918
2.8	32.9319	30.6294	28.3268	26.0242	23.7216	21.4190	19.1164	16.8138	14.5113	12.2087	9.9061	7.6038	5.3037	3.0261	.9573	.01686
2.9	32.8968	30.5943	28.2917	25.9891	23.6865	21.3839	19.0813	16.7788	14.4762	12.1736	9.8710	7.5687	5.2687	2.9920	.9309	.01482
3.0	32.8629	30.5604	28.2578	25.9552	23.6526	21.3500	19.0474	16.7449	14.4423	12.1397	9.8371	7.5348	5.2349	2.9591	.9057	.01305
3.1	32.8302	30.5276	28.2250	25.9224	23.6198	21.3172	19.0146	16.7121	14.4095	12.1069	9.8043	7.5020	5.2022	2.9273	.8815	.01149
3.2	32.7984	30.4958	28.1932	25.8907	23.5881	21.2855	18.9829	16.6803	14.3777	12.0751	9.7726	7.4703	5.1706	2.8965	.8583	.01013
3.3	32.7676	30.4651	28.1625	25.8599	23.5573	21.2547	18.9521	16.6495	14.3470	12.0444	9.7418	7.4395	5.1399	2.8668	.8361	.008939
3.4	32.7378	30.4352	28.1326	25.8300	23.5274	21.2249	18.9223	16.6197	14.3171	12.0145	9.7120	7.4097	5.1102	2.8379	.8147	.007891
3.5	32.7088	30.4062	28.1036	25.8010	23.4985	21.1959	18.8933	16.5907	14.2881	11.9855	9.6830	7.3807	5.0813	2.8099	.7942	.006970
3.6	32.6806	30.3780	28.0755	25.7729	23.4703	21.1677	18.8651	16.5625	14.2599	11.9574	9.6548	7.3526	5.0532	2.7827	.7745	.006160
3.7	32.6532	30.3506	28.0481	25.7455	23.4429	21.1403	18.8377	16.5351	14.2325	11.9300	9.6274	7.3252	5.0259	2.7563	.7554	.005448
3.8	32.6266	30.3240	28.0214	25.7188	23.4162	21.1136	18.8110	16.5085	14.2059	11.9033	9.6007	7.2985	4.9993	2.7306	.7371	.004820
3.9	32.6006	30.2980	27.9954	25.6928	23.3902	21.0877	18.7851	16.4825	14.1799	11.8773	9.5748	7.2725	4.9735	2.7056	.7194	.004267
4.0	32.5753	30.2727	27.9701	25.6675	23.3649	21.0623	18.7598	16.4572	14.1546	11.8520	9.5495	7.2472	4.9482	2.6813	.7024	.003779
4.1	32.5506	30.2480	27.9454	25.6428	23.3402	21.0376	18.7351	16.4325	14.1299	11.8273	9.5248	7.2225	4.9236	2.6576	.6859	.003349
4.2	32.5265	30.2239	27.9213	25.6187	23.3161	21.0136	18.7110	16.4084	14.1058	11.8032	9.5007	7.1985	4.8997	2.6344	.6700	.002969
4.3	32.5029	30.2004	27.8978	25.5952	23.2926	20.9900	18.6874	16.3848	14.0823	11.7797	9.4771	7.1749	4.8762	2.6119	.6546	.002633
4.4	32.4800	30.1774	27.8748	25.5722	23.2696	20.9670	18.6644	16.3619	14.0593	11.7567	9.4541	7.1520	4.8533	2.5899	.6397	.002336
4.5	32.4575	30.1549	27.8523	25.5497	23.2471	20.9446	18.6420	16.3394	14.0368	11.7342	9.4317	7.1295	4.8310	2.5684	.6253	.002073
4.6	32.4355	30.1329	27.8303	25.5277	23.2252	20.9226	18.6200	16.3174	14.0148	11.7122	9.4097	7.1075	4.8091	2.5474	.6114	.001841
4.7	32.4140	30.1114	27.8088	25.5062	23.2037	20.9011	18.5985	16.2959	13.9933	11.6907	9.3882	7.0860	4.7877	2.5268	.5979	.001635
4.8	32.3929	30.0904	27.7878	25.4852	23.1826	20.8800	18.5774	16.2748	13.9723	11.6697	9.3671	7.0650	4.7667	2.5068	.5848	.001453
4.9	32.3723	30.0697	27.7672	25.4646	23.1620	20.8594	18.5568	16.2542	13.9516	11.6491	9.3465	7.0444	4.7462	2.4871	.5721	.001291
5.0	32.3521	30.0495	27.7470	25.4444	23.1418	20.8392	18.5366	16.2340	13.9314	11.6289	9.3263	7.0242	4.7261	2.4679	.5598	.001148
5.1	32.3323	30.0297	27.7271	25.4246	23.1220	20.8194	18.5168	16.2142	13.9116	11.6091	9.3065	7.0044	4.7064	2.4491	.5478	.001021
5.2	32.3129	30.0103	27.7077	25.4051	23.1026	20.8000	18.4974	16.1948	13.8922	11.5896	9.2871	6.9850	4.6871	2.4306	.5362	.0009086
5.3	32.2939	29.9913	27.6887	25.3861	23.0835	20.7809	18.4783	16.1758	13.8732	11.5706	9.2681	6.9659	4.6681	2.4126	.5250	.0008086
5.4	32.2752	29.9726	27.6700	25.3674	23.0648	20.7622	18.4596	16.1571	13.8545	11.5519	9.2494	6.9473	4.6495	2.3948	.5140	.0007198
5.5	32.2568	29.9542	27.6516	25.3491	23.0465	20.7439	18.4413	16.1387	13.8361	11.5336	9.2310	6.9289	4.6313	2.3775	.5034	.0006409
5.6	32.2388	29.9362	27.6336	25.3310	23.0285	20.7259	18.4233	16.1207	13.8181	11.5155	9.2130	6.9109	4.6134	2.3604	.4930	.0005708
5.7	32.2211	29.9185	27.6159	25.3133	23.0108	20.7082	18.4056	16.1030	13.8004	11.4978	9.1953	6.8932	4.5958	2.3437	.4830	.0005085
5.8	32.2037	29.9011	27.5985	25.2959	22.9934	20.6908	18.3882	16.0856	13.7830	11.4804	9.1779	6.8758	4.5785	2.3273	.4732	.0004532
5.9	33.1866	29.8840	27.5814	25.2789	22.9763	20.6737	18.3711	16.0685	13.7659	11.4633	9.1608	6.8588	4.5615	2.3111	.4637	.0004039
6.0	32.1698	29.8672	27.5646	25.2620	22.9595	20.6569	18.3543	16.0517	13.7491	11.4465	9.1440	6.8420	4.5448	2.2953	.4544	.0003601
6.1	32.1533	29.8507	27.5481	25.2455	22.9429	20.6403	18.3378	16.0352	13.7326	11.4300	9.1275	6.8254	4.5283	2.2797	.4454	.0003211
6.2	32.1370	29.8344	27.5318	25.2293	22.9267	20.6241	18.3215	16.0189	13.7163	11.4138	9.1112	6.8092	4.5122	2.2645	.4366	.0002864
6.3	32.1210	29.8184	27.5158	25.2133	22.9107	20.6081	18.3055	16.0029	13.7003	11.3978	9.0952	6.7932	4.4963	2.2494	.4280	.0002555
6.4	32.1053	29.8027	27.5001	25.1975	22.8949	20.5923	18.2898	15.9872	13.6846	11.3820	9.0795	6.7775	4.4806	2.2346	.4197	.0002279
6.5	32.0898	29.7872	27.4846	25.1820	22.8794	20.5768	18.2742	15.9717	13.6691	11.3665	9.0640	6.7620	4.4652	2.2201	.4115	.0002034
6.6	32.0745	29.7719	27.4693	25.1667	22.8641	20.5616	18.2590	15.9564	13.6538	11.3512	9.0487	6.7467	4.4501	2.2058	.4036	.0001816
6.7	32.0595	29.7569	27.4543	25.1517	22.8491	20.5465	18.2439	15.9414	13.6388	11.3362	9.0337	6.7317	4.4351	2.1917	.3959	.0001621
6.8	32.0446	29.7421	27.4395	25.1369	22.8343	20.5317	18.2291	15.9265	13.6240	11.3214	9.0189	6.7169	4.4204	2.1779	.3883	.0001448
6.9	32.0300	29.7275	27.4249	25.1223	22.8197	20.5171	18.2145	15.9119	13.6094	11.3068	9.0043	6.7023	4.4059	2.1643	.3810	.0001293
7.0	32.0156	29.7131	27.4105	25.1079	22.8053	20.5027	18.2001	15.8976	13.5950	11.2924	8.9899	6.6879	4.3916	2.1508	.3738	.0001155
7.1	32.0015	29.6989	27.3963	25.0937	22.7911	20.4885	18.1860	15.8834	13.5808	11.2782	8.9757	6.6737	4.3775	2.1376	.3668	.0001032
7.2	31.9875	29.6849	27.3823	25.0797	22.7771	20.4746	18.1720	15.8694	13.5668	11.2642	8.9617	6.6598	4.3636	2.1246	.3599	.00009219
7.3	31.9737	29.6711	27.3685	25.0659	22.7633	20.4608	18.1582	15.8556	13.5530	11.2504	8.9479	6.6460	4.3500	2.1118	.3532	.00008239
7.4	31.9601	29.6575	27.3549	25.0523	22.7497	20.4472	18.1446	15.8420	13.5394	11.2368	8.9343	6.6324	4.3364	2.0991	.3467	.00007364
7.5	31.9467	29.6441	27.3415	25.0389	22.7363	20.4337	18.1311	15.8286	13.5260	11.2234	8.9209	6.6190	4.3231	2.0867	.3403	.00006583
7.6	31.9334	29.6308	27.3282	25.0257	22.7231	20.4205	18.1179	15.8153	13.5127	11.2102	8.9076	6.6057	4.3100	2.0744	.3341	.00005886
7.7	31.9203	29.6178	27.3152	25.0126	22.7100	20.4074	18.1048	15.8022	13.4997	11.1971	8.8946	6.5927	4.2970	2.0623	.3280	.00005263
7.8	31.9074	29.6048	27.3023	24.9997	22.6971	20.3945	18.0919	15.7893	13.4868	11.1842	8.8817	6.5798	4.2842	2.0503	.3221	.00004707
7.9	31.8947	29.5921	27.2895	24.9869	22.6844	20.3818	18.0792	15.7766	13.4740	11.1714	8.8689	6.5671	4.2716	2.0386	.3163	.00004210
8.0	31.8821	29.5795	27.2769	24.9744	22.6718	20.3692	18.0666	15.7640	13.4614	11.1589	8.8563	6.5545	4.2591	2.0269	.3106	.00003767
8.1	31.8697	29.5671	27.2645	24.9619	22.6594	20.3568	18.0542	15.7516	13.4490	11.1464	8.8439	6.5421	4.2468	2.0155	.3050	.00003370
8.2	31.8574	29.5548	27.2523	24.9497	22.6471	20.3446	18.0419	15.7393	13.4367	11.1342	8.8317	6.5298	4.2346	2.0042	.2996	.00003015
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8.5	31.8215	29.5189	27.2163	24.9137	22.6112	20.3086	18.0060	15.7034	13.4008	11.0982	8.7957	6.4939	4.1990	1.9711	.2840	.00002162
8.6	31.8098	29.5072	27.2046	24.9020	22.5995	20.2969	17.9943	15.6917	13.3891	11.0865	8.7840	6.4822	4.1874	1.9604	.2790	.00001936
8.7	31.7982	29.4957	27.1931	24.8905	22.5879	20.2853	17.9827	15.6801	13.3776	11.0750	8.7725	6.4707	4.1759	1.9498	.2742	.00001733
8.8	31.7868	29.4842	27.1816	24.8790	22.5765	20.2739	17.9713	15.6687	13.3661	11.0635	8.7610	6.4593	4.1644	1.9393	.2694	.00001552
8.9	31.7755	29.4729	27.1703	24.8678	22.5652	20.2626	17.9600	15.6574	13.3548	11.0523	8.7497	6.4480	4.1534	1.9290	.2647	.00001390
9.0	31.7643	29.4618	27.1592	24.8566	22.5540	20.2514	17.9488	15.6462	13.3437	11.0411	8.7386	6.4368	4.1423	1.9187	.2602	.00001245
9.1	31.7533	29.4507	27.1481	24.8455	22.5429	20.2404	17.9378	15.6352	13.3326	11.0300	8.7275	6.4258	4.1313	1.9087	.2557	.00001115
9.2	31.7424	29.4398	27.1372	24.8346	22.5320	20.2294	17.9268	15.6243	13.3217	11.0191	8.7166	6.4148	4.1205	1.8987	.2513	.000009988
9.3	31.7315	29.4290	27.1264	24.8238	22.5212	20.2186	17.9160	15.6135	13.3109	11.0083	8.7058	6.4040	4.1098	1.8888	.2470	.000008948
9.4	31.7208	29.4183	27.1157	24.8131	22.5105	20.2079	17.9053	15.6028	13.3002	10.9976	8.6951	6.3934	4.0992	1.8791	.2429	.000008018
9.5	31.7103	29.4077	27.1051	24.8025	22.4999	20.1973	17.8948	15.5922	13.2896	10.9870	8.6845	6.3828	4.0887	1.8695	.2387	.000007185
9.6	31.6998	29.3972	27.0946	24.7920	22.4895	20.1869	17.8843	15.5817	13.2791	10.9765	8.6740	6.3723	4.0784	1.8599	.2347	.000006439
9.7	31.6894	29.3868	27.0843	24.7817	22.4791	20.1765	17.8739	15.5713	13.2688	10.9662	8.6637	6.3620	4.0681	1.8505	.2308	.000005771
9.8	31.6792	29.3766	27.0740	24.7714	22.4688	20.1663	17.8637	15.5611	13.2585	10.9559	8.6534	6.3517	4.0579	1.8412	.2269	.000005173
9.9	31.6690	29.3664	27.0639	24.7613	22.4587	20.1561	17.8535	15.5509	13.2483	10.9458	8.6433	6.3416	4.0479	1.8320	.2231	.000004637

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[*] Table reproduced from U. S. Geological Survey Water-Supply Paper 887. facing p. 89

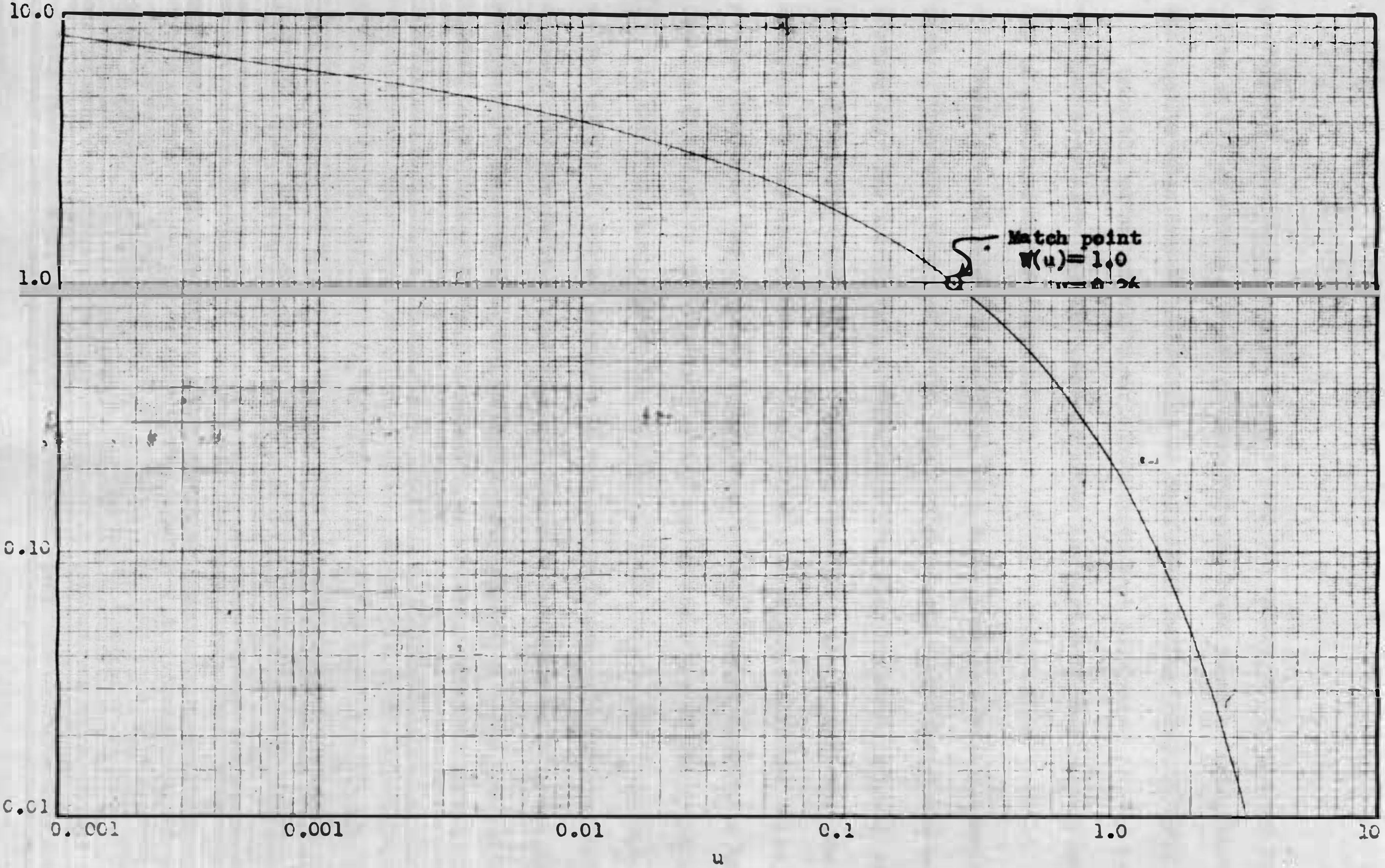

Figure 3. Type Curve Representing the Change in the Value of W(u) and u

coordinates from the common point will give the values of the plotted functions of the equations. Knowing these values, S and T may be calculated for the aquifer when constant discharge is maintained during the pump test.

Once the values of the coefficients have been determined for the aquifer, the discharge for a certain drawdown after any period of continuous pumping may be predicted by the equations.

Where several wells are confined to a small area in a multiple well system, they will have individual cones of depression overlapping one another (Figure 2). The calculation of discharge from such a system is based on the same coefficients determined by a pumping test of a single well but the calculations are complicated by the interaction of the individual wells being pumped together. The drawdown represented by each cone of depression has a cumulative effect on the drawdown at any one of the wells in the system.

In the final analysis of the results of this thesis, the discharge is calculated for 1 foot of drawdown in various sandpoint well systems. It is assumed that the suction head is equal for each sandpoint well in the system and that the drawdown will be the same in each well.

METHOD OF PROCEDURE

The site selected for conducting the pump test was located on the Thos. Martinson farm in Brookings County approximately 5 miles south and 1 mile east of Brookings, South Dakota. The exact location of the sandpoint well was on the southwest corner of E½ SW¼, T. 109 N., R. 50.

The site for this study was chosen partly because of the interest and cooperation of the owner of the property. Also, the fact that the owner had already successfully developed sandpoint wells on the farm for a water supply for his own sprinkler system indicated an extensive aquifer existed there. A possible recharge boundary for the aquifer consisted of a perennial stream flowing toward the Sioux River nearly 1 mile east of the pump site. The Sioux River itself, meandering on a southeasterly direction, formed another recharge boundary at approximately 2 miles southwest of the site. The location of impermeable boundaries was not definitely established.

On the selected site, the sandpoint well was installed at the location shown on the layout in Figure 4. The sandpoint used for the well was obtained from Edward E. Johnson, Inc., St. Paul, Minnesota. The size of the point was 2" x 30" x 36" with a slot No. 50.

First a hole was bored into the ground to a depth below the water table with a post-hole auger with an extended handle. The water table occurred at approximately 8½ feet below the surface of the ground and the hole was augered to a depth of 10 feet. A sandpoint similar to that shown in Figure 5 was coupled to a length of 2 inch iron pipe and set in the augered hole. With a driving cap on top of the pipe to protect the upper end, the sandpoint unit was driven 9½ feet into the aquifer to a depth of 18 feet.

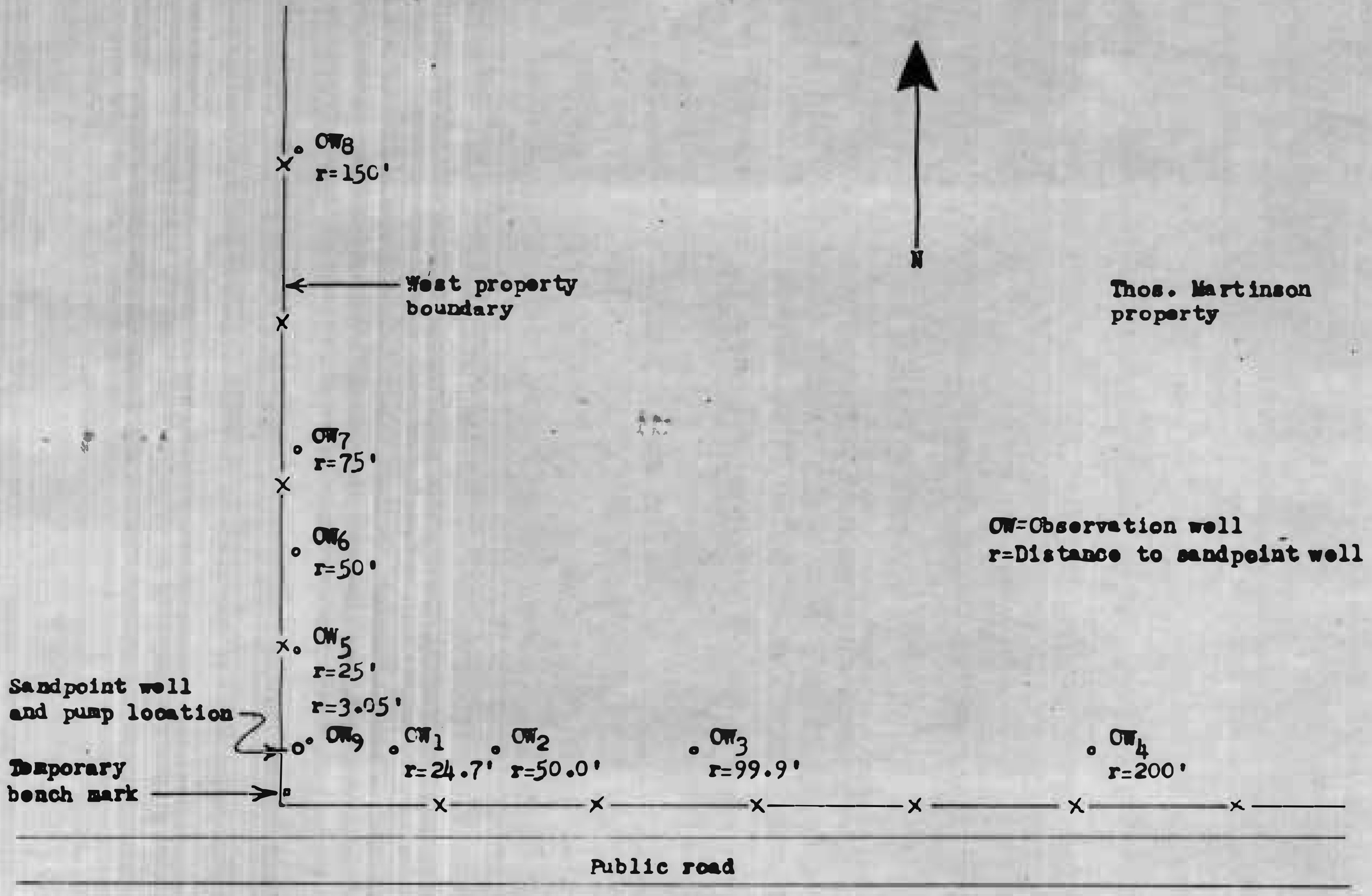

Figure 4. Layout and Location of Wells

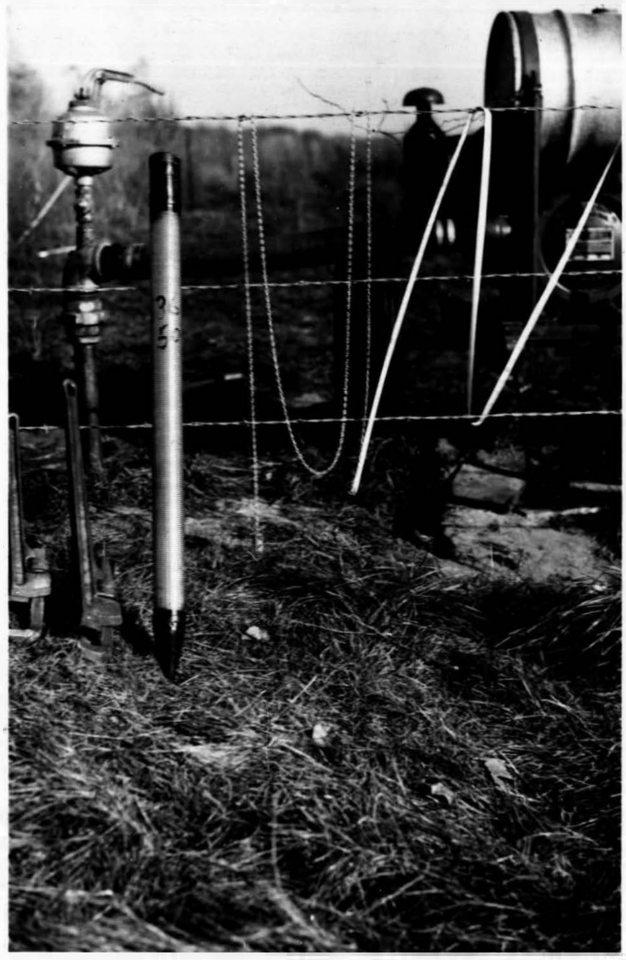

Figure 5. A 2 Inch Sandpoint, Tape Measure with Chain and Weight, and Tools Used in the Field Work

The nine observation wells were installed according to the layout in Figure 4. These each consisted of a 20 foot length of 3/4 inch iron pipe. Each pipe was driven into a hole augered to the water table in the same manner as that bored for the sandpoint well. These smaller pipes were protected on the top by a common pipe coupling and on the bottom by a solid point fashioned in the machine shop. This point was held in place by the weight of the pipe itself while the pipe was driven to the desired depth. It was then lifted off the point so the flow of water into the observation well would not be restricted. In addition to the nine observation wells in the immediate area of the sandpoint well, one well was installed north and one south of the pump site each at a distance of 1 mile.

The elevations of all the observation wells were determined and oriented with a temporary bench mark located at the southwest corner of the site. Knowing the elevations, it was possible to measure the elevation of the water table in each well. A general idea was acquired of the slope of the water table and more extensive measurements were taken to study the effects of the barometric pressure and the nature of the regional change.

To measure the level in an observation well a special method was used, based on the fact that a heavy concave object will make a distinct sound when it hits the water surface. This weight was made by pouring lead into a piece of pipe about 1 inch long that had an outside diameter small enough to easily slip inside the 3/4 inch observation well. The bottom of the weight was formed hollow and a small wire loop was inserted in the top. A length of light chain was used to attach the weight to the end of a tape measure (Figure 5). The length of the chain was adjusted so that the bottom edge of the weight when hanging freely reached exactly 10 feet below the zero mark on the measuring tape. All measurements taken ranged from 10 to 15 feet.

A portable pumping unit, consisting of a centrifugal suction pump powered by a 4 cylinder Wisconsin motor, was rented from the owner-operator of the farm and used for pumping the well. It was connected directly to the top of the sandpoint well by means of an Erickson type coupling and a length of flexible hose. Even though a driving cap had been used to protect the top of the well pipe while driving the sandpoint, the threads were stripped and had to be re-cut before attempting to connect the pumping unit.

During the long period of pumping necessary for the test, the large quantity of water pumped had to be disposed of in such a manner that it would not recharge the aquifer. About 400 feet of irrigation pipe was used to carry the discharge over a hill away from the pump site. A Sparling water meter, which had been previously calibrated, was installed on the discharge pipe from the pump (Figure 6) to measure the quantity of discharge. A valve located between the meter and the pump (Figure 6) was installed to assist in priming the pump. With the valve closed and the pump in operation a vacuum was created until the flow of water reached the valve. Then, by opening the valve, normal discharge was started.

The process of developing the well consisted of removing the fine particles of material in the aquifer around the sandpoint leaving only the coarser gravels in place so that the flow of water into the well would be restricted as little as possible. This was accomplished by accelerating and decelerating the motor causing turbulence and back-flow into the well. Considerable quantities of fine sand were carried out of the well by the flow of the water while developing the well.

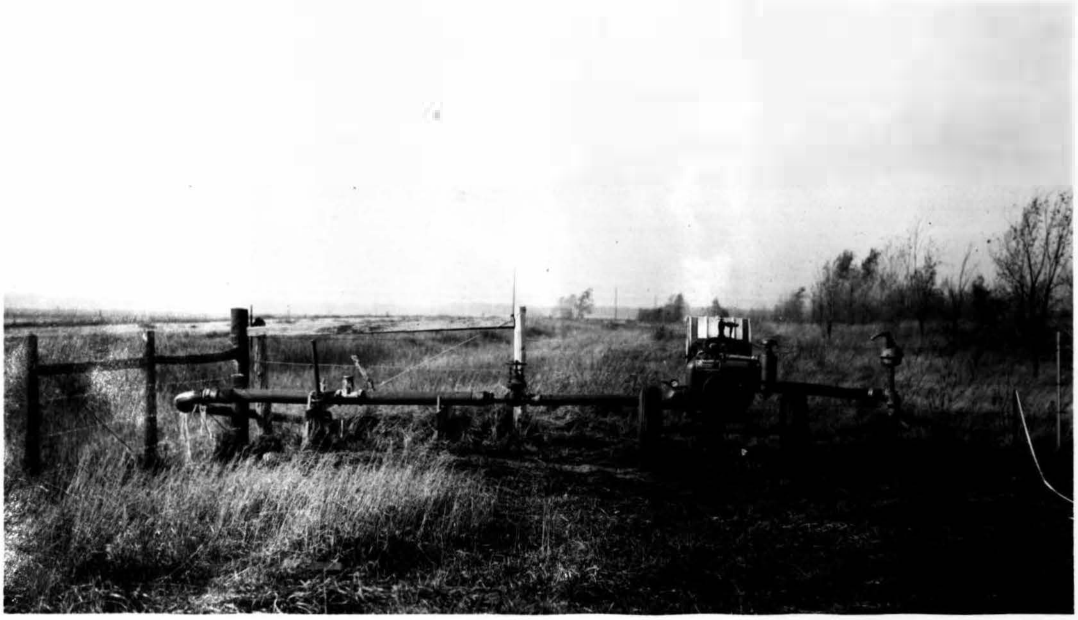

Figure 6. Pump in Operation During a Test. (Left to right) The Sparling Meter, Valve, Portable Pumping Unit, and Sandpoint Well

Figure 7. A Discharge of over 80 Gallons Per Minute

Several preliminary runs were made and measurements of the water table depression were noted in the observation wells. However, these wells did not function properly and it became necessary to develop them in a manner similar to the sandpoint well. This was accomplished by pumping water from the sandpoint well through a garden hose back into the observation wells.

The first pump test was made at a constant rate of continuous pumping over a period of 78 hours. During this period the quantity of discharge gradually diminished from approximately 41 to 37 gpm.[9] Since it was necessary to maintain constant discharge to determine the transmissibility from the data, this variation introduced considerable error.

From the experience of the operator of the farm it was known that the capacity for yield from such a well was much greater. Furthermore, it was known that such a well would yield more if it penetrated the entire aquifer. Consequently, the sandpoint was driven an additional 4 feet to a depth of 22 feet below the ground surface. It was again connected to the pump and developed as before. Several preliminary runs were made to determine the performance that could be expected under these conditions. The discharge was found to increase to above 80 gpm and to remain reasonably constant. Figure 7 illustrates a discharge of over 80 gpm. A second and more successful pump test was made at the higher discharge for a duration of 77 hours.

During the first minutes of the pump test, there was a rapid increase in drawdown in the observation wells nearest the pump which diminished as the duration of pumping continued. In order to observe this rapid change, it was necessary to have enough assistance in taking measurements so that

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[9] Gallons per minute

simultaneous readings of the water level in the observation wells could be made for short increments of time. Simultaneous readings were first taken each minute and then for increasing time changes during the initial 2 hour period. The remaining readings were taken at increasing hourly increments of time. Figure 8 shows a measurement made in the observation well at the sandpoint well and in Figure 9 the reading was taken in observation well No. 1. To obtain accurate readings the tape was always held between the thumb and forefinger and the thumb was dropped against the top of the pipe. The tape was slowly lowered until the sound of it striking the surface of the water was heard. The reading was taken at the top of the pipe when the

Figure 8. Drawdown Measurement Being Made in Observation Well No. 9

Figure 9. Drawdown Measurement Being Made in Observation Well No. 1

first sound was heard. With a little practice accuracy was acquired in making the readings.

Observations of the water surface elevation at intervals before the pump test and daily readings for a period of over 2 weeks after the test indicated that there was negligible daily change due to factors other than pumping. A previous study showed considerable depression of the water table due to the pumping from other sandpoint wells on the farm. However, the second test was not performed until the fall season and pumping for irrigation had ceased long enough so that the water table had recovered from any effects from this source.

RESULTS

Many readings of the static water table level were taken at various periods before and after the pump tests were performed. The row of observation wells extending to the north (see layout, Figure 4) was found to have a sloping water table of approximately 0.11% whereas the water table in the row of wells extending to the east was very nearly level. In analyzing the results of the pump tests, the data from wells No. 5 to 8 inclusive did not conform to the type curve of the nonequilibrium formula nearly as well as the data from the wells on the level water table. Consequently, only the data from wells No. 1, 2, 3, 4 and 9 were presented and used in obtaining the coefficient of transmissibility for the aquifer.

The data taken during the first pump test are shown in Table 2. It was necessary to apply to the data the correction for a thin aquifer which had a total thickness of 14 feet and these corrected values also appear in the table. Because the variation in discharge compared to the total discharge was great and the magnitude of the drawdown was relatively small, the data from the first pump test were erratic to the extent that they were not suitable for use in the final analysis.

The measurements of drawdown taken from observation wells No. 1 through 4 and well No. 9 for the second pump test appear in Table 3. These data were corrected for a thin aquifer in the same manner as those of Table 2. The corrected values shown in Table 3 were utilized in analysing the results where coefficients of transmissibility and storage were determined.

Observation well No. 9 was located just 3 feet from the pumped well and the water table conditions during a pump test were very unstable at this

Table 2. Discharge and Drawdown Data for Pump Test Number 1

Time since pump test started (minutes)	Discharge (gpm)	Measured (s_1) and corrected (s)* drawdown in feet						
		Obs. well$_9$		Obs. well$_1$		Obs. well$_2$	Obs. well$_3$	Obs. well$_4$
		s_1	s	s_1	s	$s_1 = s$	$s_1 = s$	$s_1 = s$
1				0.10	0.10	0.01	0.00	0.00
2				0.15	0.15	0.02	0.00	0.00
3				0.17	0.17	0.03	0.00	0.00
4				0.18	0.18	0.04	0.00	0.00
6				0.20	0.20	0.06	0.00	0.00
8				0.22	0.22	0.07	0.00	0.00
10				0.23	0.23	0.07	0.00	0.00
15				0.24	0.24	0.08	0.00	0.00
20				0.25	0.25	0.10	0.00	0.00
30		0.79	0.77	0.27	0.27	0.10	0.01	0.00
45		0.80	0.78	0.29	0.29	0.11	0.01	0.00
60	40.9	0.80	0.78	0.30	0.30	0.12	0.02	0.00
90		0.82	0.80	0.32	0.32	0.14	0.03	0.00
120	39.4	0.82	0.80	0.33	0.33	0.16	0.04	0.01
240	39.4	0.85	0.83	0.38	0.37	0.20	0.06	0.01
480	39.2	0.90	0.87	0.43	0.42	0.25	0.12	0.02
720	39.0	0.88	0.86	0.45	0.44	0.29	0.14	0.04
1140		0.93	0.90	0.49	0.48	0.32	0.19	0.08
1440	38.6	0.92	0.89	0.49	0.48	0.33	0.19	0.08
1860	37.6	0.87	0.85	0.49	0.48	0.33	0.21	0.09
2160	37.4	0.88	0.86	0.49	0.48	0.34	0.21	0.10
2880	37.6	0.85	0.83	0.48	0.47	0.33	0.22	0.11
3300	36.7	0.82	0.80	0.46	0.45	0.32	0.21	0.11
3600	37.2	0.85	0.83	0.47	0.46	0.33	0.22	0.12
4645	36.6	0.82	0.80	0.45	0.44	0.32	0.22	0.12

*$s = s_1 - s_1^2/2m$, where $m = 14$ ft.

Table 3. Discharge and Drawdown Data for Pump Test Number 2

Time since pump test started (minutes)	Discharge (gpm)	Measured (s_1) and corrected (s)* drawdown in feet									
		Obs. well$_9$		Obs. well$_1$		Obs. well$_2$		Obs. well$_3$		Obs. well$_4$	
		s_1	s	s_1	s	s_1	s	s_1	s	s_1	s
1				0.09	0.09	0.07	0.07	0.01	0.01	0.00	0.00
2				0.15	0.15	0.09	0.09	0.01	0.01	0.00	0.00
3				0.20	0.20	0.10	0.10	0.01	0.01	0.00	0.00
4		0.34	0.34	0.25	0.25	0.12	0.12	0.01	0.01	0.00	0.00
6		0.45	0.44	0.33	0.33	0.13	0.13	0.01	0.01	0.00	0.00
8		0.54	0.53	0.41	0.40	0.16	0.16	0.02	0.02	0.00	0.00
10		0.64	0.62	0.45	0.44	0.17	0.17	0.02	0.02	0.00	0.00
15		0.86	0.83	0.53	0.52	0.20	0.20	0.03	0.03	0.00	0.00
20	86.3	1.07	1.03	0.58	0.57	0.23	0.23	0.04	0.04	0.00	0.00
30	86.3	1.36	1.30	0.66	0.64	0.27	0.27	0.06	0.06	0.00	0.00
45		1.66	1.56	0.71	0.69	0.31	0.31	0.08	0.08	0.00	0.00
60	86.3	1.90	1.77	0.77	0.75	0.34	0.34	0.11	0.11	0.01	0.01
90	85.3	2.18	2.01	0.86	0.83	0.41	0.40	0.15	0.15	0.02	0.02
120	85.5	2.32	2.13	0.92	0.89	0.46	0.45	0.18	0.18	0.03	0.03
240	84.8	2.59	2.35	1.07	1.03	0.59	0.58	0.26	0.26	0.06	0.06
480	84.0	2.79	2.51	1.20	1.15	0.71	0.69	0.34	0.34	0.09	0.09
720	84.0	2.83	2.55	1.28	1.22	0.78	0.76	0.41	0.40	0.12	0.12
1200	83.8	2.91	2.60	1.38	1.31	0.88	0.85	0.49	0.48	0.18	0.18
1440	83.1	2.93	2.62	1.41	1.34	0.91	0.88	0.52	0.51	0.20	0.20
1890	81.7	2.96	2.65	1.46	1.38	0.98	0.95	0.57	0.56	0.24	0.24
2190	82.4	2.98	2.66	1.48	1.40	0.99	0.96	0.60	0.59	0.27	0.27
2880	81.7	3.05	2.72	1.52	1.44	1.03	0.99	0.65	0.63	0.30	0.30
3240	81.7	3.03	2.70	1.54	1.46	1.05	1.01	0.69	0.67	0.32	0.32
3600	81.8	3.05	2.72	1.56	1.48	1.08	1.04	0.70	0.68	0.35	0.35
4600	81.3	3.05	2.72	1.59	1.50	1.10	1.06	0.72	0.70	0.39	0.38

*$s = s_1 - s_1^2/2m$, where $m = 14$ ft.

distance from the discharging well. Therefore the data obtained from this observation well were used only in checking the coefficient of transmissibility.

ANALYSIS OF THE RESULTS

The nonequilibrium formula as previously explained is as follows:

$s = (114.6\ Q/T)\ W(u)$

$r^2/t = (T/1.87\ S)\ u$

In applying these equations to an aquifer, S and T are considered to have a constant value for that aquifer. During the second pump test Q ranged from 86.3 to 81.3 gpm (Table 3). The discharge dropped to about 85 gpm after the two initial hours of pumping so Q was assigned a constant of 83 gpm for the test.

The corrected drawdowns from Table 3, except those for observation well No. 9, were plotted against the value of r^2/t on logarithmic tracing paper to the same scale as the type curve (Figure 3). Selecting the position representing the best match, the type curve was superimposed on the plotted field data as shown in Figure 10.

For various reasons the data obtained do not always conform exactly to the type curve and judgment acquired by previous experience must be utilized in making the best fit. The greater the duration of the pump test the greater the conformity to the ideal situation; and, had this test been continued for a longer period of time, the points would eventually all have fallen very close to the type curve.

The superimposed curve now represents the coordinates of the plotted unknowns in the nonequilibrium formula since any point on the curve is a common point of the respective coordinates for both the well function and the actual data. A convenient point to select is $W(u) = 1.0$ at $u = 0.26$ on the type curve coordinates. This point falls on the coordinates $s = 0.28$ and $r^2/t = 2.1\ (10)^4$ for the drawdown data. Substituting these values in the

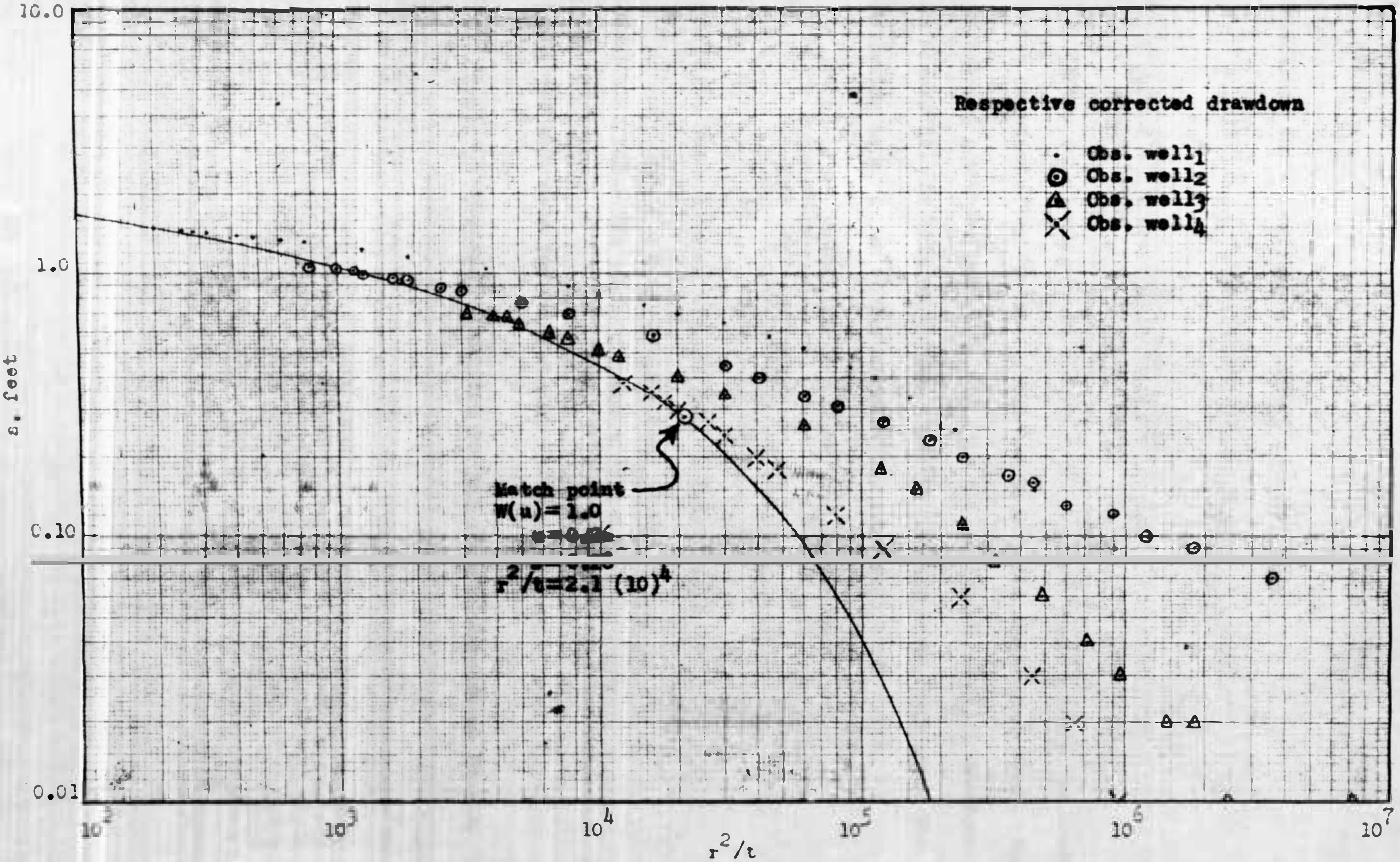

Figure 10. Plotted Field Data for Pump Test Number 2 with the Superimposed Type Curve

equations the following coefficients are obtained:

$$T=\frac{114.6\ Q}{s}\ W(u)=\frac{114.6\ (83)\ (1.0)}{0.28}=34{,}000\ \text{gpd/ft.}$$ [10]

$$S=\frac{T\ (u)}{1.87\ (r^2/t)}=\frac{3.4\ (10)^4\ (0.26)}{1.87\ (2.1)\ (10)^4}=0.225$$

After calculating S and T, these values were used to check the drawdowns obtained after 2½ days of pumping during the second pump test. The calculated drawdowns were compared with the corrected observed drawdowns in Figure 11. At this particular time the discharge was 81.8 gpm. The following is a sample of the computations involved:

At observation well No. 4, $r = 200$ ft., $t = 2.5$ days

$$u=\frac{1.87\ r^2 S}{Tt}=\frac{1.87\ (200)^2\ (0.225)}{3.4\ (10)^4\ (2.5)}=1.98\ (10)^{-1}$$

From Table 1, when $u = 1.98\ (10)^{-1}$, $W(u) = 1.231$

$$s=\frac{114.6\ Q\ W(u)}{T}=\frac{114.6\ (81.8)\ (1.231)}{3.4\ (10)^4}=0.34\ \text{ft.}$$

The results in the following table were computed by the equations shown above for each well for Q = 81.8 gpm.

Table 4. Drawdown Calculated for 2.5 Days of Continuous Pumping

Observation well	r (ft.)	u	W(u)	s (ft.)	s, observed (ft.)
4	200	$1.98\ (10)^{-1}$	1.231	0.34	0.35
3	99.9	$4.94\ (10)^{-2}$	2.479	0.68	0.68
2	50.0	$1.24\ (10)^{-2}$	3.826	1.06	1.04
1	24.7	$3.02\ (10)^{-3}$	5.228	1.44	1.48
9	3.05	$4.60\ (10)^{-5}$	9.410	2.60	2.72
At sandpoint	0.083	$3.41\ (10)^{-8}$	16.617	4.58	---

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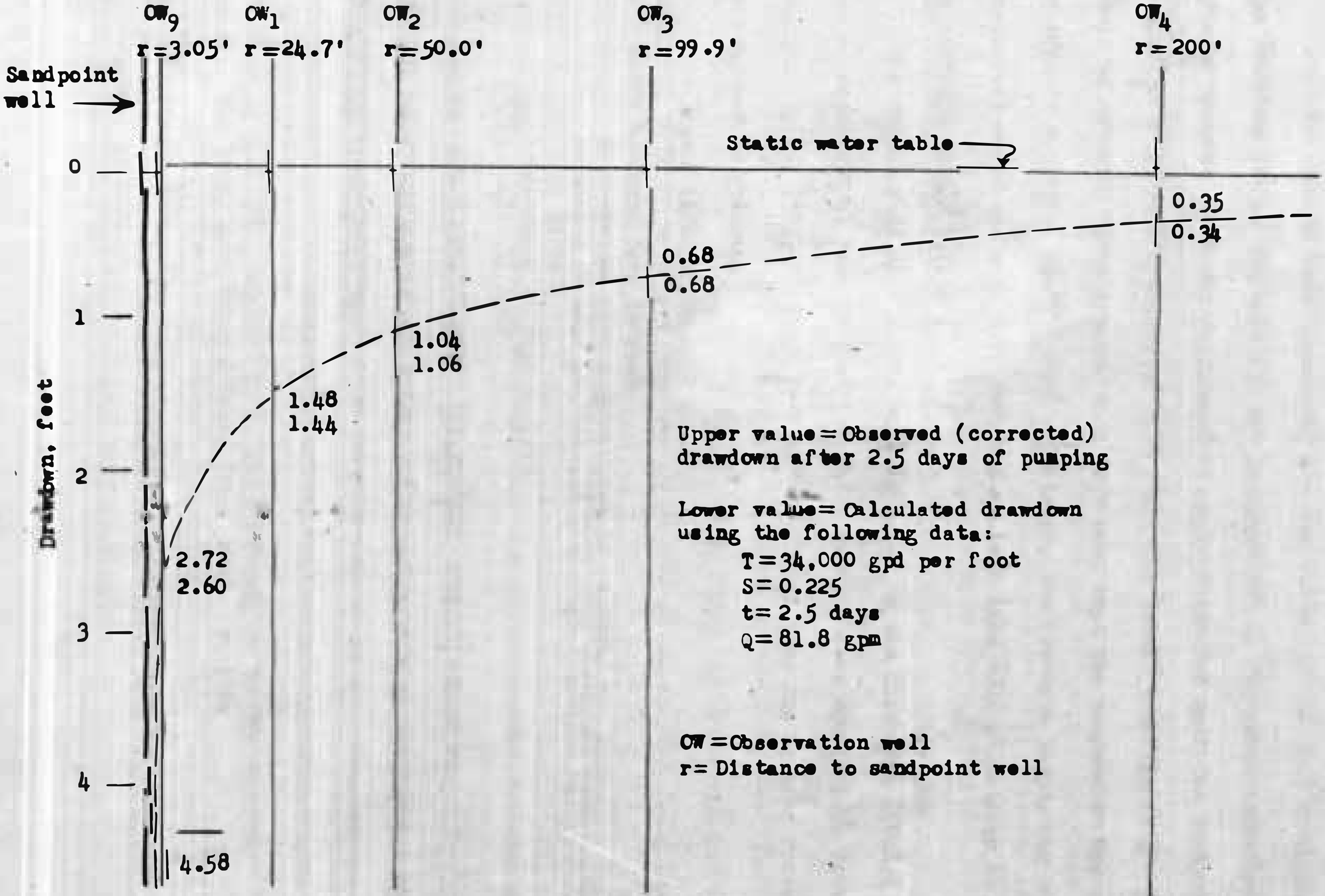
[10] Gallons per day per foot



Upper value = Observed (corrected) drawdown after 2.5 days of pumping

Lower value = Calculated drawdown using the following data:

T = 34,000 gpd per foot
S = 0.225
t = 2.5 days
Q = 81.8 gpm

OW = Observation well
r = Distance to sandpoint well

Figure 11. Comparison of Observed and Calculated Drawdowns for 2.5 Days of Continuous Pumping

Further calculations concerning the hydraulics of the well were made. The drawdown inside the well was not measured but in the above comparison a greater drawdown than the calculated value is indicated near the sandpoint. Using the calculated drawdown of 4.58 feet, the actual drawdown at the well could be expected to be greater than 5.75 feet when the correction for a thin aquifer is applied. At 100% well efficiency, the drawdown inside the sandpoint well would still be 5.75 feet and at less than 100% efficiency it would be correspondingly greater.

The velocity of flow in the well is equal to the discharge divided by the cross-sectional area of the pipe which in this case equals 8.34 feet per second. By the Darcy-Weisbach formula[11] the head loss due to pipe friction is computed as follows:

$$h_f = f\,(L/D)\,V^2/2g$$

where h_f = head loss in feet
f = numerical factor determined by velocity and pipe diameter[12]
L = length of pipe in feet (in this case estimated distance water is lifted)
D = diameter of pipe in feet
$V^2/2g$ = velocity head

and $h_f = 0.025\,(15.0/0.167)\,\left[(8.34)^2/(2)(32.2)\right] = 2.42$ ft.

The head loss due to enlargement of cross section on the suction side of the pump is computed by:[13]

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[11] King, Horace W., Wisler, C. O. and Woodburn, J. G. Hydraulics. 5th ed. New York, John Wiley & Sons, Inc. 1948. p. 182.

[12] Ibid., p. 184.

[13] Ibid., p. 203.

$$h_e = K_e\ V^2/2g$$

where h_e = head loss in feet
K_e = value of coefficient for sudden enlargement[14]

and $h_e = 0.31\ (8.34)^2/(2)\ (32.2) = 0.355$ ft.

also $H_f = h_f + h_e = 2.42 + 0.34 = 2.76$ ft.

Considering a well efficiency of 100% the total suction lift after 2½ days of pumping is equal to the sum of the drawdown, elevation of the pump above the water table, and total head loss. Let H_T and H_e represent total lift and elevation of the pump above the water table, respectively. Then

$H_T = s_1 + H_e + H_f = 5.75 + 9.5 + 2.76 = 18.0$ ft. (minimum).

The final analysis of the results for the pump test consists of the computation of two tables by the use of the coefficients determined for this particular aquifer. The first table, Table 5, lists the theoretical discharge per foot of corrected drawdown at the end of one day of continuous pumping at 100% well efficiency for various arrangements in sandpoint systems. Table 6 lists similar computations for theoretical discharge at the end of ten days of continuous pumping. The nonequilibrium formula is used in the same manner as before for computing discharge from systems of adjacent wells being pumped simultaneously except that the well function of u is adjusted to compensate for the interference of their respective cones of depression. This is accomplished by calculating a well function for the radius of each interferring well and using the cumulative well function in solving for the discharge from the well in question. The sum of the discharge for each well in the system determined in this manner is equal to the discharge for the particular system being analyzed.

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[14] Ibid., p. 208.

Table 5. Theoretical Discharge Per Foot of Corrected Drawdown for Various Sandpoint Systems After One Day of Continuous Pumping at 100 Per Cent Well Efficiency

Number of points in system	Two inch sandpoint spacing in feet						1¼ inch sandpoint spaced at 40 feet
	10	20	30	40	60	80	
1	18.9	18.9	18.9	18.9	18.9	18.9	17.8
2	27.2	29.0	30.2	31.2	32.5	33.5	29.7
3	33.0	36.8	39.4	41.4	44.5	46.9	39.6
4	37.7	43.3	47.4	50.7	56.0	60.1	48.8
5	41.7	49.3	55.0	59.7	67.3	73.2	57.5

Table 6. Theoretical Discharge Per Foot of Corrected Drawdown for Various Sandpoint Systems After Ten Days of Continuous Pumping at 100 Per Cent Well Efficiency

Number of points in system	Two inch sandpoint spacing in feet						1¼ inch sandpoint spaced at 40 feet
	10	20	30	40	60	80	
1	16.5	16.5	16.5	16.5	16.5	16.5	15.7
2	22.4	23.6	24.5	25.1	26.0	26.6	24.2
3	26.3	28.6	30.2	31.4	33.3	34.8	30.4
4	29.2	32.5	34.8	36.6	39.6	41.9	35.6
5	31.5	35.7	38.8	41.2	45.3	48.6	40.2

At the end of one day of continuous pumping, the discharge for 1 foot of corrected drawdown from a sandpoint system consisting of five 2 inch sandpoints spaced at 40 foot intervals with the pump located above the center sandpoint is computed as follows:

$T=3.40\ (10)^4$ $t=1$ day r in well$=1$ in.$=0.0833$ ft.
$S=0.225$ $s=1$ ft. no. points$=5$ spaced at 40 ft.

For center well:

$$u=\frac{1.87\ r^2\ S}{Tt}=\frac{1.87\ (0.0833)^2\ (0.225)}{3.4\ (10)^4\ (1.0)}=8.59\ (10)^{-8}$$

$W(u)=15.693$ (From Table 1)

For 40' radius well:

$$u=\frac{1.87\ (40)^2\ (0.225)}{3.4\ (10)^4\ (1.0)}=1.98\ (10)^{-2};\ W(u)=3.365$$

For 80' radius well: $W(u)=2.036$
For 120' radius well: $W(u)=1.320$
For 160' radius well: $W(u)=0.865$

For center well:

$$Q=\frac{s\ T}{114.6\ W(u)}=\frac{(1.0)\ (3.4)\ (10)^4}{114.6\ [15.693+2(3.365)+2(2.036)]}=11.2 \text{ gpm}$$

For well half way out:

$$Q=\frac{(1.0)\ (3.4)\ (10)^4}{114.6\ [15.693+2\ (3.365)+2.036+1.320]}=11.5 \text{ gpm}$$

For well at end of system:

$$Q=\frac{(1.0)\ (3.4)\ (10)^4}{114.6\ [15.693+3.365+2.036+1.320+0.865]}=12.75 \text{ gpm}$$

Discharge from the five point system:

$$Q_t=11.2+2\ (11.5)+2\ (12.75)=59.7 \text{ gpm}$$

This discharge is the quantity listed for a five point system in the column in Table 5 for a 40 foot spacing.

To assume the same drawdown in all the sandpoints in a system, the suction lift at the top of each well must be equal. This condition will exist only if the connecting pipe has a large enough diameter so that the head loss due to pipe friction is negligible. Under normal operating conditions, it would not be economically practical to install pipe of such diameter that all head loss in a system spaced 60 or 80 feet would be eliminated; consequently, the results presented in Tables 5 and 6 must be adjusted for any variation in the suction lift at the top elevation of the wells in such a system.

The values of the discharge presented here for the various systems are valid for an aquifer identical in nature to the one on which this pump test was conducted. The results are calculated for definite conditions and are subject to change due to any variation in these conditions.

SUMMARY AND CONCLUSIONS

The discharge that a well penetrating a water-bearing aquifer can produce depends upon the capacity of the strata to store and transmit substantial quantities of ground water. The rate that water flows through the saturated aquifer under certain qualifications determines its coefficient of transmissibility. If the drawdown and duration of pumping are measured, the quantity of discharge from any well can be calculated by Theis' nonequilibrium formula using the average coefficients of transmissibility and storage previously determined for the aquifer being pumped.

In the pump test conducted on the Sioux River aquifer, the coefficients of transmissibility and storage were determined, respectively, as 34,000 gpd per foot and 0.225 or 22.5%. These values were used in computing the tables of discharge from various sandpoint systems after one and ten days of continuous pumping.

The following conclusions are presented:

1. Approximately the same discharge can be obtained by operating five 2 inch sandpoints spaced 20 feet as by operating four spaced 40 feet. This means that 40 feet of connecting pipe can be eliminated by installing the additional sandpoint at 20 feet and, unless the diameter of pipe for the 40 foot spacing were increased, the head loss due to friction would be greater. Similar comparisons can be made for other spacing combinations.

2. A 1½ inch sandpoint system will discharge almost as much water as a 2 inch system under the same conditions. However, the maximum drawdown in the former will be decreased sharply due to additional head loss caused by pipe friction.

3. The quantity of discharge will gradually decrease as the duration of continuous pumping is increased. After a long period of continuous pumping the area of the cone of depression in an infinitely wide aquifer becomes very extensive, and the rate of decrease in the quantity of discharge slowly diminishes until it can no longer be determined by ordinary linear measurements.

4. Discharge is directly related to drawdown and any increase in drawdown will increase the discharge for a system. Then, if maximum lift is the factor limiting drawdown, it should be possible to increase the discharge of a system by lowering the elevation of the pumping unit and decreasing the distance to the water table.

The coefficients of transmissibility and storage determined for this aquifer are based on one pump test only. They are representative of one sample and to obtain coefficients that characterize the strat more accurately, several pump tests should be conducted.

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