Thesis



# Flow and Yield of Ground-Water.

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Introduction: Water as it falls upon the earth as rain, disposes itself in several different ways. Some of it flows off directly into streams and other bodies of water; some of it is evaporated again directly from the surface upon which it falls, and is carried of in the air. Still another part percolates through the soil and rocks, and it is the latter that constitutes the principle part of ground-water.

Surface wells have been in existence for thousands of years, and have been a very common source of supply to families. But until recently ground-water has not been considered an important source of supply for large towns and cities.

Today some of the largest cities in the world are supplied from this source. London in England, Paris in France, and Brooklyn in this country are examples of cities which are partly supplied from wells. At the present time engineers recognize ground-water as one of the important available sources of supply in many cases.

It is my purpose in the following pages, to discuss the yield of ground-water under various circumstances.

Since the entire source of ground-water is the water that is precipitated from the atmosphere as rain, it follows that the amount of ground water to be obtained from any given area depends upon the amount of rainfall upon that area, or more strictly upon all the area near enough to influence the flow in the given area. Starting with a simple case, let us see what is the maximum amount of ground water to be expected from a given area (A), which is influenced only by the rain that falls upon it. Experiments and observations shows that about 20 percent of total rainfall percolates into the soil and forms ground-water.

Now allowing an annual rainfall of 20 inches we have 5 inches that percolate into the ground, If we assume that all of this can be drawn from the ground again, we have, $Q = \frac{A \times 5}{12}$ where Q equals the quantity of water in cubic feet, and A equals the area in square feet.

Hence assuming the simplest conditions, we see that to determine the quantity of water possible to be obtained, it is necessary to know the extent of the watershed and rainfall. The extent of the watershed depends upon the topography of the country and geological formation.

If the geological formation of the ridge separating two slopes is broken up and full of seams and crevices we may, and probably will, have to a certain extent, the water flowing from one side of the ridge to the other. This is not usually the case, generally the boundary ridges are impervious to the flow of water, and then the only available water is that which falls as rain within the limits of the water shed.

The amount of rainfall varies very greatly in different countries and in different parts of the same country. Mr. G. J. Symonds has deduced the following facts from his observations. First:- The wettest year will have a rainfall of nearly $\frac{1}{2}$ as much again as the mean, and the dryest year will have $\frac{1}{3}$ less than the mean.

The two dryest consecutive years will have

$\frac{1}{4}$ less than the mean; the dryest 3 consecutive years will have $\frac{1}{5}$ less than the mean. It is evident that in estimating the supply for a town, the dryest year should be taken to indicate the amount of water that can be relied upon.

The table on the next page gives the mean monthly rainfall near Boston for the average of a large number of years. The minimum rainfall was 27.2" in 1822. The maximum was 67.7" in 1863 and the mean annual rainfall is 46.67". These figures agree approximately with the conclusions deduced by Mr. Symonds.

The rainfall as distributed among the seasons is as follows:— Winter 11.64", Spring 12.16", Summer 11.35" and Autumn 11.52".

Boston Cochituate report of rainfall, --- avarage for a large number of years.

Table I.

| Month | Inches of r. f. |
|---|---|
| January | 3.90" |
| Febuary | 3.76" |
| March | 4.29" |
| April | 4.10" |
| May | 3.77" |
| June | 3.29" |
| July | 3.68" |
| September | 3.45" |
| August | 4.38" |
| October | 3.75" |
| November | 4.32" |
| December | 3.95" |
| Mean Annual Rainfall -- | 46.67" |

# Table of rainfall at Rugby, Warwickshire England.

## Table II.

| | 1855 | 1856 | 1857 | 1858 | 1859 | 1860 | 1861 | 1862 | 1863 | 1864 | 1865 | 1866 | 1867 | 1868 | Mean of 14 years |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| January | .07 | 2.42 | 2.64 | .28 | 1.09 | 2.56 | 1.37 | 2.29 | 2.07 | .92 | 2.64 | 2.15 | 3.09 | 2.34 | 1.85 |
| February | 1.00 | 1.65 | .76 | .98 | 1.46 | .84 | 1.52 | .79 | .45 | 1.45 | 2.17 | 2.58 | 1.42 | 1.54 | 1.30 |
| March | 1.22 | .67 | 1.89 | .62 | 1.41 | 1.89 | 2.07 | 3.58 | .31 | 2.81 | 1.22 | 1.22 | 2.57 | 2.08 | 1.68 |
| April | .57 | 1.69 | 2.51 | 2.47 | 1.94 | 1.21 | .55 | 1.56 | 1.41 | 1.48 | .68 | 1.23 | 2.37 | 1.40 | 1.50 |
| May | 1.19 | 2.78 | .85 | 1.92 | 1.23 | 2.96 | 1.03 | 2.34 | .44 | 1.39 | 1.62 | 1.40 | 2.39 | .53 | 1.58 |
| June | 2.41 | 1.40 | 2.23 | 1.36 | 2.51 | 5.36 | 1.88 | 3.32 | 3.72 | .87 | 2.47 | 2.33 | 3.25 | .26 | 2.38 |
| July | 6.82 | 1.53 | 2.26 | 1.76 | 1.39 | 1.40 | 4.62 | 1.89 | .66 | .28 | 3.85 | 3.14 | 2.46 | .30 | 2.31 |
| August | 1.22 | 1.65 | 3.84 | 2.22 | 2.23 | 3.16 | .86 | 1.90 | 2.02 | .73 | 3.47 | 4.08 | 3.43 | 3.34 | 2.44 |
| September | 1.03 | 1.52 | 3.87 | 2.17 | 1.79 | 2.57 | 1.97 | 3.28 | 2.23 | 1.37 | .24 | 6.20 | 3.49 | 2.16 | 2.42 |
| November | 4.46 | 1.72 | 2.15 | 2.16 | 2.42 | 2.29 | 1.23 | 2.59 | 2.13 | 1.67 | 4.60 | 1.97 | 2.69 | 2.28 | 2.46 |
| October | 1.16 | 1.35 | 1.56 | .45 | 1.88 | 2.01 | 2.51 | .75 | 1.47 | 1.65 | 2.29 | 1.74 | .49 | 1.44 | 1.52 |
| December | .67 | 1.67 | .61 | 2.04 | 1.75 | 1.36 | 1.22 | 1.30 | 1.10 | 1.79 | 1.29 | 1.87 | 1.86 | 5.48 | 1.71 |
| Yearly total | 21.82 | 20.55 | 25.20 | 18.43 | 21.10 | 27.55 | 26.83 | 25.19 | 18.51 | 16.41 | 25.94 | 29.91 | 29.51 | 23.15 | 23.15 |

Table II shows the mean monthly and mean annual rainfall for 14 years at Rugby Warwickshire England.

Taking the minimum rainfall for a single year, viz:-- 1864, and the mean for 14 years, we see that it agrees very well with Mr. Symonds rule, the minimum being approximatly ⅓ less the mean. The maximum rainfall for the 14 years occurs in 1866 and equals 29.91". This does not agree with the rule, being about ¼ greater than the mean, instead of ½. In making an estimate for water supply, we are concerned only with the minimum rainfall as I have before stated.

The next question we must consider is the amount of water which percolates into the ground to form ground water. This, of course, must vary with the kind of ground upon which the precipitation occurs. Averages of experiments over large areas show that in England, approximately ½ the rainfall evaporates ~~or~~ is taken up by plants, and the other half flows off or percolates into the ground. This is not even approximately true except when we take into consideration large areas. Evidently if the surface of the ground is ledgy or very rocky a large part of the rain will flow off directly into the streams. On the other hand if the surface upon which the rain falls is flat and the soil sandy, a large part of

The rainfall will be secured as ground water. Between these two limits there are all degrees of infiltration.

Some experiments upon infiltration by Mr. Dickinson, an English Engineer are perhaps as reliable as any that have been made. The aparatus used was a Dalton gauge, and consisted of a wooden vessel formed of staves, hooped and painted like a barrel, and sunk into the ground, so that the upper edge was near the upper surface level. The bottom was saucer shaped and of lead, a pipe of the same material serving to conduct away the filtered water to a graduated gauge. The materials with which the vessel was filled were, at the top a layer of ten inches of the ordinary soil of the district — a sandy, gravelly loam — then a thickness of about fifteen inches of coarse gravel, gradually becoming coarser as it approached the main mass, which was composed of clean coarse gravel.

Table III gives the results of Mr. Dickenson's experiment extending over a period of 33 years. Table IV. gives the avarage results of Dr. Dalton's experiment extending over 3 years, Mr. Dickenson's experiments, and Mr. Charnock experiments extending over a period of 5 years. The apparent difference in the results may be explained by the difference in material used to fill the gauges. Dr. Dalton used the common surface soil of the district (new red sandstone) which contains a

# Table III.

| Month | Mean Monthly Rainfall | Mean Monthly Infiltration | % of Infiltration to r.f. |
|---|---|---|---|
| January | 2.417" | 1.531" | 63.3 |
| February | 1.650" | 1.120" | 68.0 |
| March | 1.720 | .850 | 49.5 |
| April | 1.670 | .230 | 13.6 |
| May | 2.000 | .115 | 5.75 |
| June | 2,160 | .086 | 4.00 |
| July | 2.370 | .074 | 3,10 |
| August | 2.440 | .009 | ,37 |
| September | 2,410 | .110 | 4,57 |
| October | 2,970 | .710 | 24.00 |
| November | 2.530 | 1.440 | 57,2 |
| December | 1.910 | 1.190 | 62.3 |
| | 26,247 | 7.465 | 28.5 |

Table IV.

| Observers | Mean annual fall of rain on the surface during the time of the experiments. | Mean annual quantity of rain filtered through three feet of ground. | Proportion per cent. |
|---|---|---|---|
| | Inches | Inches | |
| Dr. Dalton | 33.5 | 8.39 | 25.0 |
| Mr. Dickinson | 26.25 | 7.465 | 28.5 |
| Mr. Charnock | 24.60 | 4.82 | 19.6 |

good deal of clay, and would probably be very absorbent and retentive. Mr. Dickinson took the lighter gravelly loam overlying the chalk, and common in the tertiary and secondary districts around London; while Mr Charnock employed the heavier magnesium limestone soil of Yorkshire; and further his experiments having reference to a special agricultural question, the soil was accasionally stirred. In this latter instance, therefore, the evaporation would be increased, which, joined with the fact of this soil being much more argillaceous, would account for the infiltration being less than in the other experiments.

* Mr Symonds says:-- "Experiment on percolation show that of an avarage of 30 years rainfall, in which the annual rainfall was 27.843 inches, 6.519 inches passed through 3 feet of soil and 10.65 inches through the same depth of chalk. In 10 years out of a mean rainfall of 81.451 inches, 14.04 inches passed through 20" of soil and 18.241" through 60" of soil. It cannot be

* Sanitary Engineer, March 18th, 1886.

too often insisted on that, in the case of water supply from porous soils, avarages are in the highest degree illusory. The minimum or at best the lowest avarage for three successive years is the utmost we can depend upon." Taking the triennial period of 1862-64, he found that with a rainfall of 22" only 3½" penetrated to depth of 8 feet, and from 1869-71 out 25" only about 4" reached that depth. Through chalk in the former period the percolation reached 5.2".

Table III is interesting as showing the small percentage of percolation during the summer months. From this it will be seen that in order to insure a continual supply from the ground water of any given area, the ground must act as a reservoir to store up the water from the months when the percolation is greatest.

From the foregoing discussion it appears that, although the percentage of percolation varies considerably under different conditions, we might reasonably estimate the amount of infiltration, in an ordinary sandy soil of moderate slope, to be from 15 to 25 % of the rainfall per annum.

We shall next consider the amount of water that certain kinds of geological formations will contain when saturated. Table V

# Table V.

| Lithological Character | Quantity of water absorbed by one cubic foot. | | Quan. perm. thro. equal portions of sand in 1 hour |
|---|---|---|---|
| | Cubic inches | gallons | Cu. inches |
| Fine sand, light-colored, slightly argillaceous | 669 | 2.41 | 1.8 |
| " " rather more " | 712 | 2.56 | 5.7 |
| Coarse mixed bright-green and yellow sand. | 626 | 2.25 | |
| Fine sand, light ash yellow | 723 | 2.60 | 5.1 |
| Very fine light-colored sand, rather argillaceous | 774 | 2.79 | 1.5 |
| " " and argillaceous sand, light green | 853 | 3.07 | |
| " " and less argillaceous sand, | 821 | 2.96 | 3.6 |
| " " " argillaceous sand. | 842 | 3.03 | |
| " " " more argillaceous sand | 883 | 3.18 | 1.2 |
| " " white and pure silicious sand. | 518 | 1.87 | |
| Fine bright ochraceous silicious sand | 615 | 2.21 | 9.6 |
| Bright ferruginous siliceous sand, rather coarse | 712 | 2.56 | 18.0 |
| Fine yellow sand, slightly argillaceous. | 734 | 2.64 | 14.4 |
| Rather coarse light-green sand. | 605 | 2.18 | 4.5 |
| Very coarse sand with small pebbles of quartz. | 605 | 2.18 | 7.5 |

shows the absorbent power of some of the principal water-bearing strata.

It is seen from the table that a cubic foot of sand will hold from two to three gallons of water, or from 2/7 to 1/2 their bulk. It is also evident that it is not the purest sands that hold the most water. The presence of clay increases the capacity for holding moisture, and at the same time it rapidly diminishes the permeability of the strata.

The same experimenter, Mr. Prestwick, who has given the above results, also found that common garden mould absorbs about 2.6 gallons of water per cubic ft. In different qualities of sandstone and limestone rock he found the absorbant power to vary from 20 to 55 grains of water per cubic foot.

Mr Symonds states that the new red sandstone of Liverpool will absorb $\frac{1}{22}$ of its weight of water of which $\frac{1}{2}$ will drain away. Loose sand and chalk he estimates will absorb $\frac{1}{9}$ to $\frac{1}{2}$ of their weight, or two gallons per cubic foot; and that Oolite and limestone will absorb 12 to 14 pints.

Gravel consisting of small water-worn stones or pebbles, intermixed with grains of sand, has ordinarily twenty to twenty-five percent of voids. Marl composed of limestone grains, clay, and silicious sands, has from ten to twenty percent of voids, according to the proportions and thoroughness of admixture of its constituents. Pure clays have innumerable interstices, not easily measured, but capable of absorbing, after thorough drying, from eight to fifteen percent of an equal volume of water. The water contained in clays is so fully subject to laws of molecular attraction, owing to the minuteness of individual interstices, that great pressure is required to give it appreciable flow.

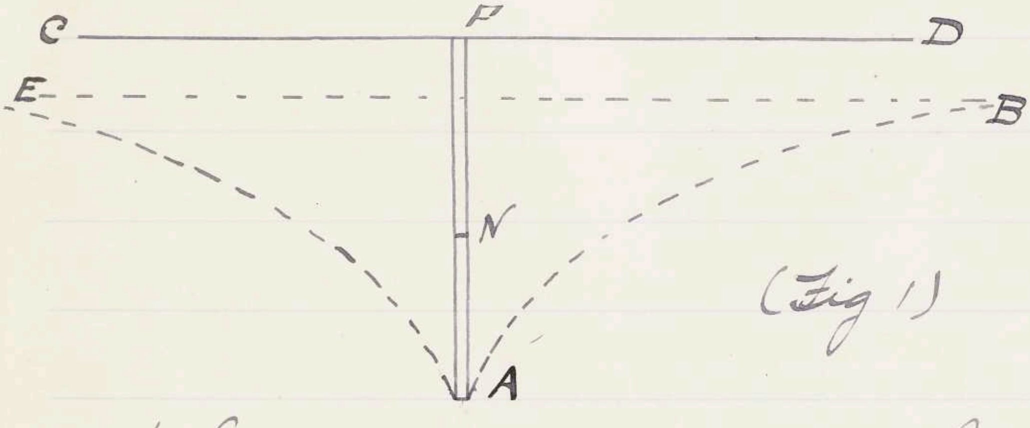
Water flows with some degree of freedom through sandstones, limestones, and chalks, according to their textures, and they are capable of absorbing from ten to twenty percent of their equal volume of water.

The primary and secondary formations, according to geological classification, as for instance, granites, serpentines, troppeans, gneisses, mica-slates, and argillaceous schists, are classed as impervious rocks, as are, usually, the strata of pure clays that have been subjected to great superincumbent weight. The crevices in the impervious rocks, resulting from rupture, however, gather and lead away, as natural drains, large volumes of the water of percolation. The free flow of the percolating water through springs and wells, is limited not only by the porosity of the strata which it enters, but also by their inclination, curvature, and continuous extent, and by the imperviousness of the underlying strata, or plutonic rock: This matter however I will discuss under the subject of "Underground flow".

Underground flow: When rain percolates into the ground it sinks to the level of the "water-table", that is, to the level at which the ground-water stands at that point. In other words the rain sinks to a point, vertically below which the ground is saturated and vertically above which the earth is not saturated. In a wet time the plane of saturation or "water table" follows approximately the contour of the surface of the ground, but in a dry time it may vary considerably from it; in any case the amount it will depart from the shape of the ground surface depends upon the resistance of the ground to the flow of water through it, and upon the time that has elapsed since a rainfall has occurred. Evidently if the ground was composed of large rocks and boulders from the surface of the ground to sea-level, any rain that fell upon it would in a short time form a level plane at the same elevation as the sea; and again if no rain fell for a long time, all the water already in the ground would tend seek the level of the sea, and would do so absolutly if the time were long enough.

The inclination of the underlying water surface is independent of the strata beneath. Some experiments upon porous soil by Mr. J. H. Shedd at Newton Mass. show that under a head of 8' the flow will not exceed 2' per hour. The slope of ground water depends upon the amount of interstitial friction and upon the slope of the ground surface. If a river flows through any area that largely determines the level of the water table. When the plane of saturation falls so as to be flatter than the inclination of the valley through which a stream flows, it dries up; on the other hand rain may be sufficient to raise the water table to the surface of the ground, even on a hillside. When the bottom of a valley is uneven, and the slope of the water surface nearly corresponds to the mean of that of the valley, the phenomenon is seen of a stream appearing and disappearing alternately. In the Sacramento Valley the slope of the ground water surface is about 4' in a mile; in the neighborhood of Taunton Mass there is a fall of 14' in a thousand. Sometimes, owing to lack of homogeneity, veins of water are formed in which the flow may be quite rapid.

If a well is sunk into the ground below the water line, and water be pumped out, the water level will be lowered. If the pumping is continued the level of the ground water will sink, until it falls to the level of the bottom of the well. Let CD represent the surface

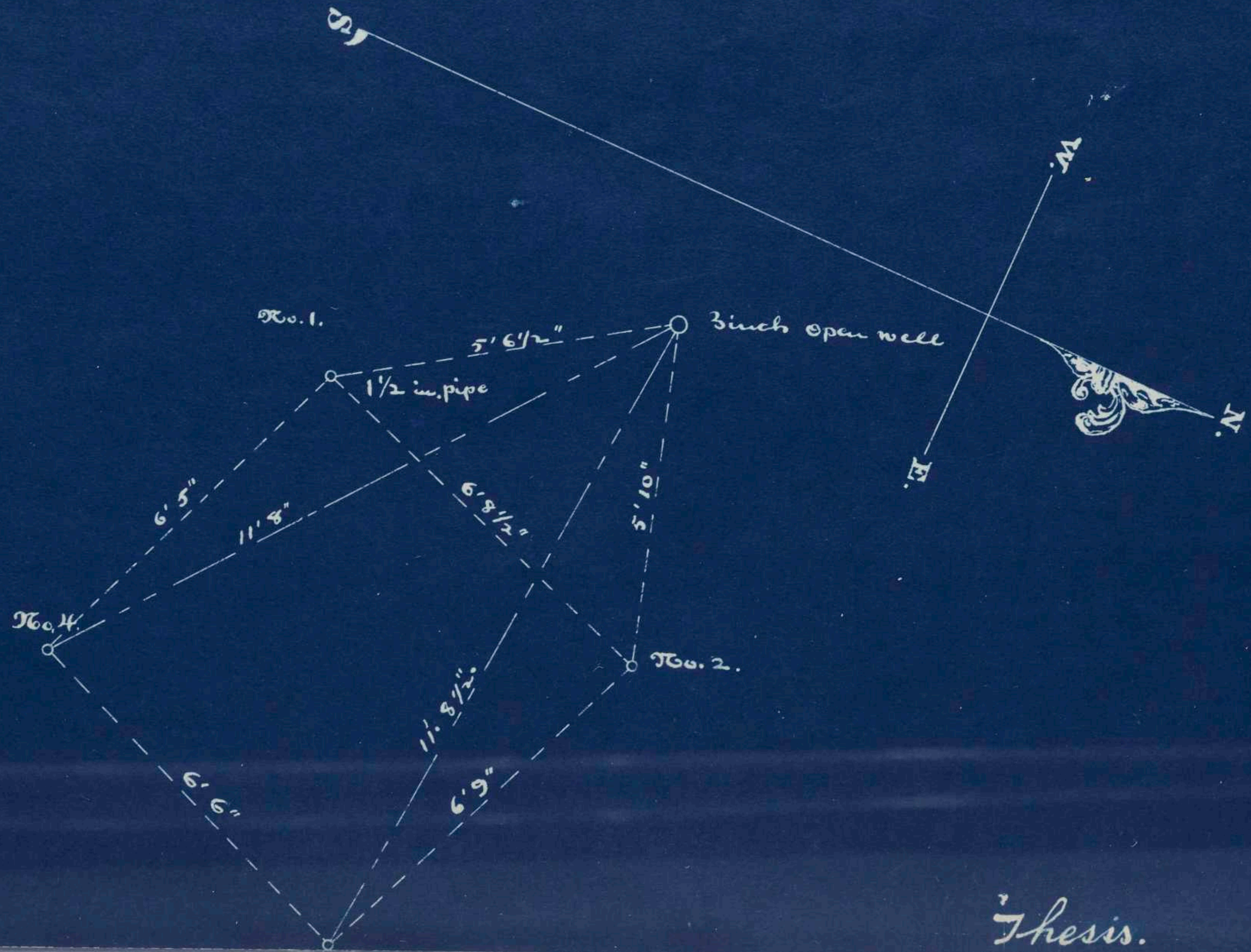



(Fig 1)

of the ground, and EB the level of the water table. Now if water be pumped from the well FA, the surface of saturation will take some curve as AB. The shape of this curve and the distance it extends in the direction EB before it becomes tangent to E B depends upon the conditions of equilibrium between the force of gravity and interstitial friction. Some writers claim that in a closed well, a partial vacuum is formed within the well when pumping, and that this causes an increased flow owing to the difference between the atmospheric pressure and the pressure in the well. That is to say, that we have the atmospheric pressure plus gravity tending to force the water into the well. I do not think think this is true, unless the water in the well has not sunk to the bottom of the well, but stands at some point as at N (fig 1). If the water in well has fallen to A, the only water that can get into the well, is that dependent upon the slope AB; and obviously any vacuum at A in the well can have no effect upon the flow down the slope AB, except perhaps for a few inches from A. I shall next give some experiments upon the flow of water in wells by Mr John C. Hoadley. These experiments were performed with five wells at Malden Mass.

Figure (9) shows the relative position of the wells. No.s 1, 2, 3 and 4 are 1½ inch driven wells. The open well is a 3" gas pipe sunk to depth of 30', and a 1½" gas pipe let down inside through which to pump the water. A steam pump was arranged so that it could be attached to any one of the wells. The water

# Malden Experiments.




Thesis.

pumped was run through a meter and the amount registered. After going through the meter it was carried in suitable troughs to some distance from the place of pumping so that it could not get back to the ground water. An hourly record was kept of the height of water in all the wells.

Tables VI, VII, VIII, IX and X. show the change of height of ground water at different wells.

Table VI gives the height of water before regular pumping was commenced, and indicates that the water was nearly on a level in the different wells. The reason for the 3" well being lower than the others is this;--

# Table VI.

| Well | Ht. of water at beginning |
|---|---|
| 3" well | 32.17' |
| No. 4 | 32.41' |
| No. 1 | 32.39' |
| No. 2 | 32.38' |
| No. 3 | 32.39' |
| Avarage | 32.393' |

When pumping was stopped on May 20, at 11 o'clock the meter registered 56968 cubic feet, and when pumping was commenced again on May 21, at 2 o'clock the meter registered 57000. The pump had been thus run enough to register 32 cubic feet in trying the pump after getting up steam before taking the measurments.

Table VII.

| Time | No. 4 | No. 1 | 3" well | No. 2 | No. 3 |
|---|---|---|---|---|---|
| 2 A.M. | 32.41 | 32.39 | 32.17 | 32.38 | 32.39 |
| 3 A.M. | 31.90 | 31.76 | 29.94 | 31.86 | 31.90 |
| Difference | .51 | .63 | 2.23 | .52 | .49 |

Table VII shows the fall of water after two hours pumping, indicating a fall of .63 and .52 of a foot in the two nearest wells, and of .51 and .49 of a foot in the two fartherest wells. A slope has been thus formed in the ground water, extending some ways beyond the most remote wells.

## Table VIII.

| Time | No. 4 | No. 1 | 3" well | No. 2 | No. 3 |
|---|---|---|---|---|---|
| 2 A.M. | 32.41 | 32.39 | 32.17 | 32.38 | 32.39 |
| 12 M. | 31.46 | 31.32 | 29.50 | 31.41 | 31.45 |
| Difference | .95 | 1.07 | 2.67 | .97 | .94 |

Table VIII gives the fall after 10 hours pumping, and shows about the same slope as table VII but at a lower level.

## Table IX.

| Time | No. 4 | No. 1 | 3" | No. 2 | No. 3 |
|---|---|---|---|---|---|
| 3 A.M. | 31.90 | 31.76 | 29.94 | 31.86 | 31.90 |
| 12 M. | 31.46 | 31.32 | 29.50 | 31.41 | 31.45 |
| Difference | .44 | .44 | .44 | .45 | .45 |

Table IX shows the fall of

water after the first hour, pumping for 9 hours, and also shows that all the wells were lowered alike within .01' = 1/8", and hence a uniform slope was maintained. This confirms the fact that there was was a constant flow at the pump, and shows that the uniform flow was maintained by a uniform slope of water surface.

Table X.

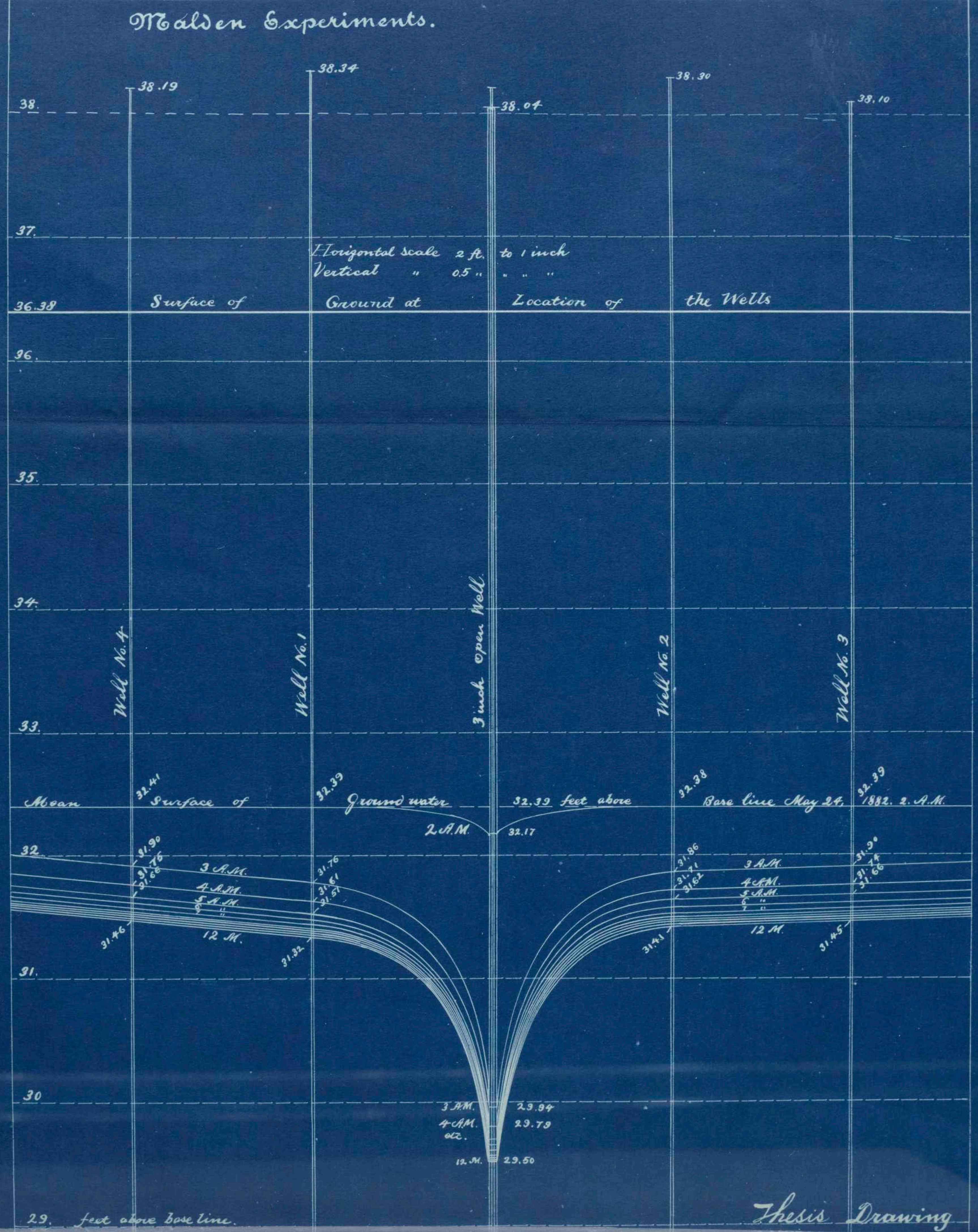
| Time | No. 4 | No. 1 | 3" well | No. 2 | No. 3 |
|---|---|---|---|---|---|
| 6 A.M. | 31.61 | 31.47 | 29.64 | 31.57 | 31.60 |
| 12 M. | 31.46 | 31.32 | 29.50 | 31.41 | 31.45 |
| Difference | .15 | .15 | .14 | .16 | .15 |

Table X indicates the same thing as table IX, and also shows that, at 6 o'clock, the height of water as well as the slope was reaching a condition just suitable to supply a constant flow.

During the experiment of 10 hours the nearly uniform rate of delivery was 2313 gallons per hour. Experiment No. 2 on the 8" open well gave practically the same results as No. 1. Experiments of 10 hours duration were performed on each of the four other wells.

Figure (3) shows the results of experiment No. 1 graphically, and needs no explanation.

Table XI gives the yield of water in gallons per hour from each of the five wells. The difference in yield was partly due to the different kind of ends used


Malden Experiments.
38.19
38.34
38.04
38.30
38.10
38.
37.
Horizontal scale 2 ft. to 1 inch
Vertical " 0.5 " " " "
36.38 Surface of Ground at Location of the Wells
36.
35.
34.
33.
Well No. 4
Well No. 1
3 inch open Well
Well No. 2
Well No. 3
32.41
32.39
32.38
32.39
Mean Surface of Ground water 32.39 feet above Base line May 24, 1882. 2. A.M.
2 A.M. 32.17
32.
31.90
31.76
31.66
31.46
3 A.M.
4 A.M.
5 A.M.
6 "
12 M.
31.76
31.61
31.51
31.32
31.86
31.71
31.62
31.41
3 A.M.
4 A.M.
5 A.M.
6 "
7 "
12 M.
31.90
31.74
31.66
31.45
31.
30
3 A.M. 29.94
4 A.M. 29.79
etc.
12 M. 29.50
29. feet above base line.
Thesis Drawing

## Table XI.

| No. 1 | No. 2 | No. 3 | No 4 | 3" open | 3" closed |
|---|---|---|---|---|---|
| 1779 | 2153 | 2458 | 2010 | 2313 | 2115 |

on the pipes in the several wells, and also probably from a variation in the permeability of the soil.

The water bearing strata in these experiments was sand and gravel.

In regard to these experiments Mr. Hoadley says: — "I am not disposed to magnify the differences noticeable as they are, in these results. Some variation is always to be expected in repeating physical experiments, and it is only by taking an avarage of many such experiments that exact deductions can be drawn. I can however say with certainty, that these experiments do not indicate any increase of yield in consequence of driving or forcing a pipe into the ground to and into the ground water without removing any earth upward, over over the insertion of similar tubes into holes in the ground made for them by removing upward all the earth in their way by any means whatsoever. These experiments therefore confirm in the most conclusive manner all that is known of the forces producing and regulating the inflow of water from the ground to and into wells to be drawn out by pumps or otherwise, namely, that but one force operates to produce such inflow, that is, the force of the earths gravitation, that such force acts by producing a slope in the surface of the ground water, and that the steepness of this slope and its particular form are dependent on the interstitial friction of the soil and on the rapidity with which water is drawn from it."

The Newark Aqueduct Board having under consideration the question of an additional water supply, had some investigations made upon some driven wells in the neighborhood of Newark. The wells were driven 40' deep into a strata of "boulder drift", which is very well adapted to holding ground-water.

The following are some of the facts found by experiment, and some of the questions discussed, by the water commissioners.

These wells averaged 650 000 gallons per 24 hours. The fact that the water did not at any time rise to within 40' of the surface, showed that the source was not in any elevated district at a distance. The water-bearing strata varied from 20' feet in thickness at the river, to 2 feet back at the hills, and averaged about 7'. The area of watershed was about 2 square miles, and the maximum bulk this strata would hold, was found to be 30% of its volume, or a total storage capacity of 878,169,600 gallons. The avarage daily supply to Newark, in 1878, was 7,280550 gallons; hence the total amount of water possible to be stored would last 120 days.

From some English experiments, 10" to 15" per annum is estimated to percolate the surface in red-sandstone regions; in this climate, probably not so much would be collected on account of evaporation; assuming 12" collectable from this surface of 2 sq. miles, the avarage annual amount collectable cannot exceed 1,140,000 gallons per day, and to collect this quantity every drop would have to be intercepted. For a permanent supply not more than one half this amount can be depended upon. For a constant draught in good open gravel it is estimated that the diameter of the base of the cone, is about 50 times the depth of the well. A well 40' deep would have a circle of influence of 72 acres, containing 42000000 cubic feet; at 25% saturation this would give 7850000 gallons. This shows the uselessness of driving wells too near together.

The Commissioners, after discussing the points just mentioned, decided that a ground supply would insufficient and impracticable, and abandoned that means of obtaining a water-supply.

A well at Prospect Park Brooklyn affords an illustration of the lowering of ground-water by a constant draught. The well was constructed in 1869. The elevation of the water-table at that time was 15.6 feet above the sea-level and the elevation was 14.55 feet above. In April, 1870 water was pumped for two weeks, the yield being 866030 gallo per 24 hours, and the water-table was reduced in elevation to 14.25 feet above sea-level. Regular pumping was begun in June, 1870. The effect has been as shown by table XII, and we see that an average draught of 304000 gallons per day, has permanently lowered the ground-water 5 feet in 8 years.

# Table XII.

| Year | gallons per day | Avarage table elevations |
|---|---|---|
| 1870 | 300000 | 14.15' |
| 1871 | 272000 | 13.04' |
| 1872 | 437000 | 10.56' |
| 1873 | 228000 | 11.29' |
| 1874 | 333000 | 10.70' |
| 1875 | 294000 | 9.83' |
| 1876 | 281000 | 9.83' |
| 1877 | 252000 | 9.21' |
| Avarage | 304000 | |

I shall next give a somewhat detailed discription of an investigation of ground-water supply at Malden Mass. by Mr Albert F Noyes the city engineer of Newton. Mr. Noyes is, I believe, considered an authority the subject of underground-water, and hence the conclusions drawn by him have considerable weight. The investigation of Mr. Noyes is of a tipical nature and for this reason I take considerable space to discuss it.

On the next page is a sketch of the plant as it exists at the present time. The accompanying map shows the location of the wells.

12 of these wells were used to pump from during the experiments of Mr Noyes. 7. test pipes were low-

ered at different places to test the effect of pumping, also 2 pipes belonging to Mr. Eaton, who owned the land, were used for this purpose.

In order to still further determine the effect of pumping upon the level of the ground water, observations were made also on all the wells lying within the water-shed so far as possible, and the height in all refered to a common base.

In order to prevent the question being raised as to whether the water was actually conveyed away and not pumped over again, a wooden flume of 2" spruce plank with an open space of 10" high and 12" wide was laid, at a grade of .3%, from the pumping station to a point just east of the Faulkner station.

Table XIII gives the quantity of water pumped, the vacuum in the wells, and the rainfall, for each day of a 90 days test. The rainfall used was not that taken upon this water-shed, but was taken from the Lynn water-works observations, the difference is not sufficient to introduce any appreciable error into the calculations.

Eaton Meadows, so called, where these wells are driven, are about grade 9' or about 4' above mean high tide.

Topographically considered, Eaton Meadows form a part of a valley having an easterly direction from Malden station to the Meadows,

| Day of Test | Number of hours | Gallons Pumped | Vacuum | Rain or Snow |
|---|---|---|---|---|
| Dec. 18, 1886 | | | | |
| 1 | 24 | 811782 | 18 3/4 | 0.57" |
| 2 | " | 828492 | 19 1/2 | 0.15 |
| 3 | " | 865734 | 19 3/4 | 0 |
| 4 | " | 868002 | 20 1/4 | .27 |
| 5 | " | 852944 | 20 | .11 |
| 6 | " | | 21 | .02 |
| 7 | " | 873402 | 19 1/2 | 0 |
| 8 | " | 800884 | 19 1/2 | 0 |
| 9 | " | 841201 | 19 1/2 | .01 |
| 10 | " | 838433 | 19 | .37 |
| 11 | " | 799500 | 18 1/2 | .07 |
| 12 | " | 806606 | 19 | .62 |
| 13 | 20 hrs. 30 m | 807603 | 19 | 0 |
| 14 | 24 | 857096 | 19 3/4 | 0 |
| 15 | " | 843482 | 20 | .25 |
| 16 | " | 847938 | 19 1/2 | 1.28 |
| 17 | " | 827812 | 20 | 0 |

| Day of Test | Number of hours | Gallons Pumped | Vacuum | Rain or Snow |
|---|---|---|---|---|
| 18 | 24 | 811090 | 20 | 0 |
| 19 | " | 861584 | 21 | .09 |
| 20 | 19h-0 | 676716 | 20 | 0 |
| 21 | 22-2 | 826278 | 19 | 0 |
| 22 | 24 | 745578 | 20 | 0 |
| 23 | " | 818825 | 20 | .08 |
| 24 | " | 814460 | 18 | .05 |
| 25 | " | 799724 | 18½ | .11 |
| 26 | " | 798415 | 19 | 0 |
| 27 | 22h-15 | 751590 | 18½ | 0 |
| 28 | 22-55 | 746841 | 19¼ | .42 |
| 29 | 24 | 803763 | 21½ | 0 |
| 30 | " | 681503 | 16 | .09 |
| 31 | " | 796792 | 20 | 0 |
| 32 | " | 790950 | 19½ | 1.00 |
| 33 | " | 702417 | 20 | .02 |
| 34 | " | 777808 | 19½ | 0 |

| Day of Test | Number of hours | Gallons Pumped | Vacuum | Rain or Snow. |
|---|---|---|---|---|
| 35 | 24 | 738276 | 21 | 0 |
| 36 | 23.-20 | 826901 | 22 | 0 |
| 37 | 24 | 653902 | 8 | 0 |
| 38 | 20-25 | 587255 | 0 | .03 |
| 39 | 24 | 887754 | 22 | 0 |
| 40 | 23-0 | 839544 | 22½ | .70 |
| 41 | 24 | 825956 | 22½ | 0 |
| 42 | " | 850050 | 22 | 0 |
| 43 | " | 830300 | 22½ | 0 |
| 44 | 23-30 | 820743 | 24 | 0 |
| 45 | 24 | 738156 | 21 | 0 |
| 46 | 22-0 | 877384 | 0 | 0 |
| 47 | 21-11 | 743587 | 20 | 0 |
| 48 | 24 | 886193 | 22 | 0 |
| 49 | " | 871592 | 23½ | 0 |
| 50 | " | 895640 | 24 | .45 |
| 51 | — | 884712 | 23¾ | 0 |

| Day of Test | Number of hours | Gallons Pumped | Vacuum | Rain or Snow |
|---|---|---|---|---|
| 52 | 24 | 894 982 | 24 | 0 |
| 53 | .. | 890 472 | 24 | .06 |
| 54 | .. | 899 605 | 24 | .04 |
| 55 | .. | 926 383 | $24\frac{3}{4}$ | 0 |
| 56 | .. | 917 542 | $24\frac{1}{2}$ | .30 |
| 57 | .. | 907 698 | $24\frac{1}{2}$ | .52 |
| 58 | . | 980 801 | $24\frac{1}{2}$ | 0 |
| 59 | . | 894 669 | $23\frac{3}{4}$ | 0 |
| 60 | .. | 853 745 | 22 | 0 |
| 61 | .. | 868 967 | 23 | 0 |
| 62 | .. | 888 699 | 24 | 0 |
| 63 | .. | 858 547 | 24 | 0 |
| 64 | .. | 807 837 | 24 | 0 |
| 65 | .. | 859 841 | 24 | 0 |
| 66 | 18-40 | 502 483 | 20 | .90 |
| 67 | 0 | | | |
| 68 | 0 | | | |

| Day of Test. | Number of hours | Gallons Pumped | Vacuum | Rain or Snow. |
|---|---|---|---|---|
| 69 | 17–20 | 608019 | 23 | 0 |
| 70 | 24 | 822987 | 21¼ | 0 |
| 71 | 16–0 | 539458 | 19½ | .75 |
| 72 | 0 | | | |
| 73 | 21–48 | 747813 | 22½ | 0 |
| 74 | 24 | 867399 | 22½ | 0 |
| 75 | " | 859759 | 22 | 0 |
| 76 | " | 861642 | 21½ | 0 |
| 77 | " | 837648 | 21¾ | .08 |
| 78 | " | 869617 | 22½ | 0 |
| 79 | " | 855974 | 22¼ | 0 |
| 80 | " | 854583 | 22 | 0 |
| 81 | " | 851503 | 22 | 0 |
| 82 | " | 845614 | 22 | 0 |
| 83 | " | 860821 | 22½ | 0 |
| 84 | " | 879446 | 22½ | 0 |
| 85 | " | 888048 | 24¼ | 0 |

| Day of Test. | Number of hours | Gallons Pumped | Vacuum | Rain or Snow. |
|---|---|---|---|---|
| 86 | 24 | 862 668 | 21 | 0 |
| 87 | " | 789 904 | 20 3/4 | 2.55 |
| 88 | " | 831 611 | 21 | .35 |
| 89 | " | 900 368 | 21 | 0 |
| 90 | " | 724 490 | 0 | 0 |

when it takes a southeasterly direction, and broadens into what is known as the Lagun meadows. It constitutes the part of the bottom of the valley and has two main outlets, one in an easterly direction, by a brook running across Lynn Street and Broadway to the Pine river; a second by a brook northerly, crossing under Eastern Ave. and Railroad


MAP OF THE
CITY OF MALDEN
PUBLISHED BY
W. A. GREENOUGH & CO.
DIRECTORY PUBLISHERS
No 28 OLIVER ST. BOSTON.
1890
Scale 720 Feet to the Inch.
GEO. H. WALKER & CO. LITH. BOSTON
TOWN OF MELROSE
TOWN OF MEDFORD
TOWN OF EVERETT
TOWN OF REVERE
W. 1
W. 2
W. 3
W. 4
W. 5
W. 6
W. 7
OAK GROVE
MALDEN CENTRE
MAPLEWOOD
LINDEN
HIGHLANDS
EDGEWORTH
FOREST DALE CEM.
HOLY CROSS CEMETERY
Holmes Grove
Reservoir
Gravel Bank
Pumping plant
BOSTON & MAINE RAILROAD
EASTERN DIVISION B. & M. R. R.
Saugus Branch
MEDFORD BRANCH R. R.
Boston Rubber Shoe Co.
N. E. Flint Sand Paper Co.
U. S. Naval Ord. Dept.

and from thence westerly into Malden river. A third outlet may under certain conditions exist by a brook crossing Broadway near Eastern Ave. and thence East and North of the cemetary to Pine river.

Underlying this tract of land is rock with its surface outcropping at points, but dipping northerly and southerly toward these valleys. Underlying the rock is a loose sand and gravel which must readily absorb the water falling upon it until it reaches the rock bottom, when it must be shed towards and through the valley. This valley is bounded on the north by a range of hills cut up by high lateral valleys and are known as Bakers hills, and Linden Highlands. On the south and southeast it is bounded by Belmont hill and a range extending east through the town of Everett and Revere. This range is also cut by high lateral valleys, having a water-shed north and south. Just East of Faulkner station, near Cross St., spurs from the two hills approach each other so closely as to reduce the valley to very narrow limits. Baker's hill is a rock formation and the soil upon it is mostly compact gravel and must shed rapidly the water that falls upon it.

Belmont hill is underlaid with trap rock, which crops out at numerous points. This southerly range of hills is covered for a considerable depth with a compact gravel which absorbs readily the water which falls upon it, and the flow through it is very slow.

The level of the water in the driven wells before the beginning of the test was 4", and on April 13, the date of the last pumping, 16" above the surface water, showing that if the clay bed, which by the borings was found to underly the meadow, was impervious, the supply beneath it could be but slightly higher than the meadow. The difference of height of the water at beginning of the test and the latter date, may be due to the greater amount of ground-water flowing. But the extra head may be no more than would be necessary to over-come the friction which the water would encounter in coming to the surface from the coarser strata below through the more compact overlying strata.

A very rapid lowering of the level of water when the pumps were started, and the rapid recovery when they were stopped, would indicate that the strata of coarse material, through which the water comes, must be thin and that it draws upon a much thicker strata in the immediate neighborhood. The level of the water in the test wells, driven into the surface soil, was not effected by the pumping, but the lower ends must have been in a small strata of clay; for on filling the pipes with water it did not run off even when left for several days.

Referring to table XIII we see that from Dec. 17th to Jan. 7th, a period of 22 days, it rained or snowed on 16 days, a precipitation of 8.81" in 97 hours and 40 minutes (The duration of storms is not in the table). This amount of precipitation caused an increase in the level of the water in all the wells near the base and on the slopes of the hills, that would indicate that under these conditions of precipitation and temperature, there was an infiltration in excess of the amount pumped or in excess of the ground-water.

From Jan. 7, to Feb. 20, at which time the pumps were stopped by the flooding of the station, there was a constant lowering of the water in most of the wells upon which observations were made; showing a lowering of from 2 to 7 feet in the level of the ground-water over most of the water-shed, and a total lowering of the ground-water in the first 66 days of the test of from to 1 to 3 feet.

On starting the pumps Feb. 22, a three days run showed a continued lowering of the water level. From Feb. 25 to Feb. 27, there occured a second interruption in the continuity of the pumping. From Feb. 27th there was a gradual lowering of the level of the water over the most of the area until the close of the test, although the infiltration of the surface water was nearly equal to the amount pumped. Had pumping been continuous during the test there would probably have been a greater infiltration; from the level of the water being lower, less water would have run of from the surface. From the foregoing facts we may easily conclude that the water-shed and receiving area in its present physical condition is sufficient to furnish a supply of from 800000 to 1000000 gallons per 24 hours, from Dec. 1st to May 1st.

The area supplying the meadows

, or which can be made tributary to them by lowering the level of the ground-water is considered by Mr. Noyes to be substantially as follows:-- The area directly tributary to the wells, 519 acres.

The area tributary with the pumps working under normal conditions, 572 acres.

The area tributary only after long continued pumping and when the level of the ground-water has been kept at a low level for a considerable time, 955 acres.

The total possible tributary area, 1986 acres.

Mr. Noyes concludes, that the ground flow from the meadows is through the valley easterly to the Pines river, and northwesterly to the Malden river. That the clay bed extends somewhat uniformly over the bottom of the valley to the east and is under-laid by a strata of coarse gravel immediately overlying the rock bed; but it does not extend to the foot of the hills, where there is a wide strip of porous material receiving the water being shed slowly through the formation composing the hills.

It also receives a considerable proportion of the infiltration of the surface soils of the highlands.

From observations made after the pumping test, the slope of the water table under normal conditions was found to be from 5 to 7 feet per mile. As the draught upon the ground-water increases in amount, this slope increases; but as the level of the ground-water is reduced, a greater area may be drawn upon, thus maintaining the yield somewhat uniform, until the full area contributing to the supply has been drawn upon.

The dip of the bed rock seems to be somewhat uniform through the valley to the east, into and through the Saugus meadows. Borings made in the meadows showed a formation very similar to that encountered at the wells, except that the bed rock was 127 feet from the surface, which could not have been above grade 5'.

As previously stated the level of the meadows is about 5' above high tide and about 10' above mean tide. From observations repeatedly made of the level of the ground-water in the immediate vicinity of tide water, it has been found to closely approximate to mean tide.

While the strata of coarse material lying below the bed of the ocean may form an easy passage for surface water through them, the water in the ocean holds back the fresh water lying below its mean tide level. As a certain amount of head is required to force to an outlet, any excess of water which may be in the ground, the ground-water assumes a gradually rising slope, depending upon the compactness of the strata and the amount of water flowing through them.

In this way a storage reservoir is formed in the ground equal to the area which may be made tributary to it within the limit of the draught of the pumps.

From extended observations made of the amount of rainfall filtering into the ground during different portions of the year, it has been found that during the months of July, August, and September, evaporation takes place so rapid, either from the surface of the earth or from vegetation, that but little, if any, of the water falling upon the surface, becomes ground-water. The greatest absorption of ground-water, is during the months of January, February and March, and the other six months form a mean between these two.

From this it will appear that storage must furnish most of a water-supply for the summer months; this storage can only be drawn upon to depths equal to the suction lift of the pumps in their immediate vicinity, and this decreases in proportion to the slope of the ground-water.

With a pumping plant placed in the meadows at grade 10, and having a lift of 27 feet, the lowest level from which water could be drawn, would be grade -17.

As previously stated the normal slope of the ground-water is 7' in a mile; the area controlled by the waters of the ocean, Mr. Noyes estimates to be from 300 to 500 acres, thus forming a subterranean reservoir.

As a portion of this storage area may be occupied by clay beds or other impermeable material, for the purposes of our estimate, we will assume it to be 300 acres. As about eight feet of head is lost in the immediate vicinity of the pumps, and allowing for the ground slope, Mr. Noyes estimates "an average depth of 5 feet as being available."

All soils, as we have before

seen in this paper, have a capacity for absorbing a certain amount of water variously estimated from 33% for coarse gravel, to 10 or 15% for fine and more compact sands. As a portion of the material composing a part of this area is somewhat compact we may estimate a storage capacity of 10%. This capacity with an available depth of five feet, makes a storage of about 00 000 000 gallons, which may be increased slightly by a ground flow from the hills and a small infiltration from the rainfall.

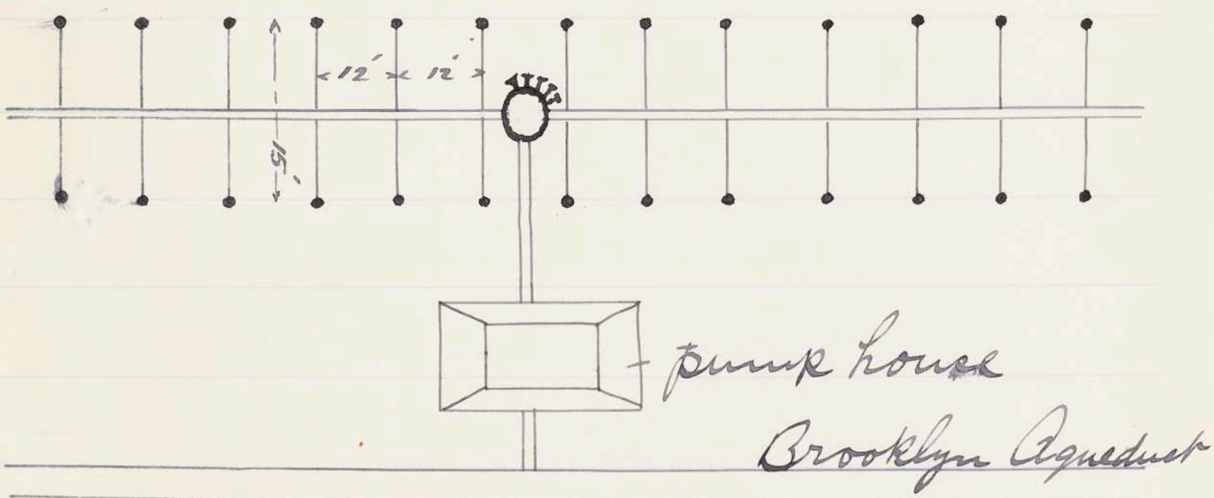
The following is a summary of Mr Noyes conclusions as to the quantity of water available within this water-shed, under its present state of development:-

"During the months of January, Febuary, and March, from 800000 to 1000000 gallons per day. During April, May, June, November, and December from 500000 to 800000 gallons per day without drawing upon the storage in the basin; and that during the months of July, August ~~and~~ September and October, by including the ground flow from the hills, the infiltration from the rainfall during that period, and by drawing upon the storage area, about 500000 gallons per day."

In order that a greater area of ground may be drawn upon at at the lower levels, I would suggest that in establishing a pumping plant and well system, the wells be sunk at a greater distance from the central station".

As an illustration of the fact, mentioned on page 2 of this paper, that a ridge between two water-sheds may not entirely stop the flow of water between them, it may be here stated that when pumping was commenced at the present pumping plant, the wells in Revere were lowered; Revere being situated on the opposite side of a ridge from Malden.

The largest driven well plant in this country, so far I know, and one of the most successful is in Brooklyn N. Y. Messrs. Andrews & Co. put in two plants yielding 18000000 gallons daily. This comes from 460 two inch tubes driven from 40 to 70 feet deep into gravel deposits. On a trial test these wells have furnished 27000000 gallons per 24 hours. The tubes occupy a space 800 feet long and 15 feet broad. The arrangement is shown below.




Test wells were sunk on

four sides of the plant and extended out 4000 feet from the pump house. Observations were made during three months. At a distance of 4300 feet from the plant the level of the water-table was reduced 6", at a distance of 2800 feet the level was reduced 2'-2", and within 800 feet the level was lowered 4'-8". When the pumps were stoped all the levels were restored.

In all explorations thus far it has been found that the gravel beds available for water are not continuous over indefinite areas nor of uniform thickness, but certain beds and certain channels in certain beds appear to constitute the underground waterways and require systematic exploration.

At Syracuse N. Y. 17 feet above canal level, 32 wells were sunk to a depth of 40 feet. 24 of these wells were of 6" pipe, and 8 were of 4½" pipe. The 6" pipes were connected to two 600 foot collecting mains; The 4½" pipes were connected to a 400 foot-main, each leading to a steam pump.

The geological structure was as follows:— Topsoil, 10 feet of clay and loose gravel free from water; then 6 feet hard pan impervious to water and last 22 feet of a shalley water-worn gravel saturated with water under a head of about 8 feet. The slope of the ground water was about 3 feet to the mile towards the canal. Pumps were run 60 days, pumping an am avarage 600000 gallons per day. The ground-water was lowered 4½ feet on an avarage over a circle whose diameter equals a mile. After the pumping stoped it took 45 days for the basin made by the pumping, to fill up again. The wet season of the year (Sept. and Oct.), and the exist=ance of a rock ridge at the head of the valley led the engineer, Mr Croes, to think that the basin was not deep seated or extended and that it would not be suf-ficient for a supply to Syracuse.

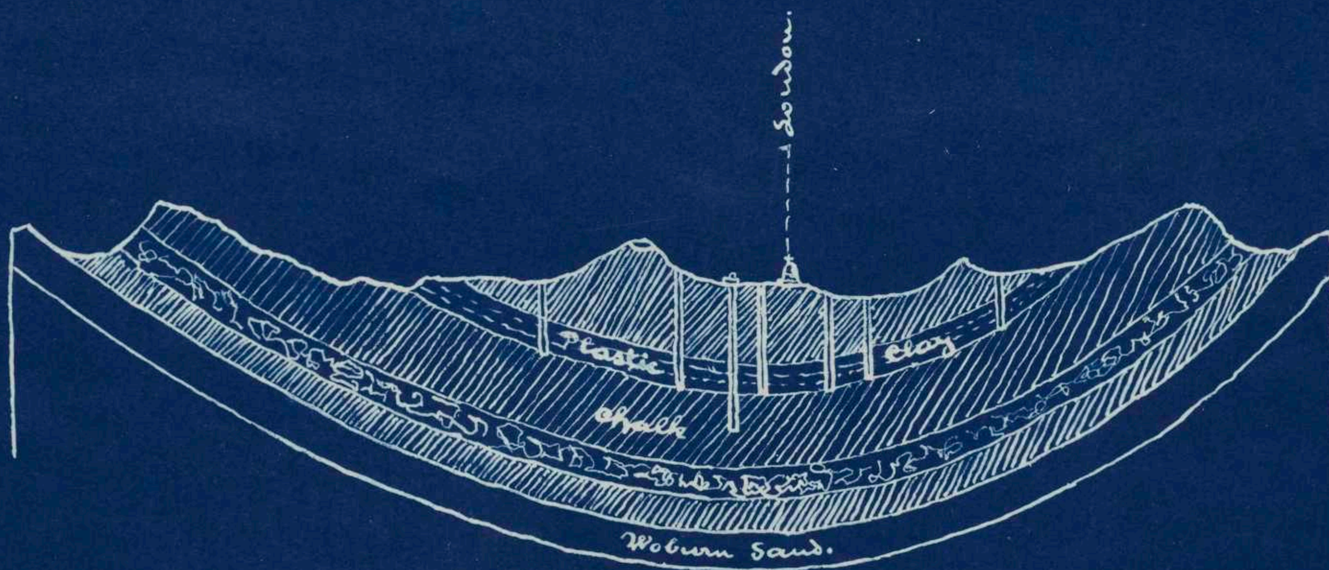
Filter Galleries: But little requires to be said regarding the yield from filter galleries; nearly all the statements made in regard to the yield from driven wells applies to filter galleries equally as well. They are dug usually along the bank of a river, and are supplied by the flow of the ground-water towards the river. They are not supplied by the water from the river as many people suppose, although when the level of the water table falls to nearly that of no flow there is some flow from the river to the gallery. The reason that there is not a greater flow from the river is probably due to the fact that the bottom is covered with silt and the interstices in the gravel near the surface of the river bed are filled with fine mud and silt which clog up the water passages and prevent much water flowing through.

The water supply of The Hague Holland is collected from 1600 acres of land by means of a filter gallery. The gallery is 3½ miles long and 10 to 30 feet wide and gives a daily yield of 600000 gallons. The ground is sandy and water table varies from 8½ to 20 feet above sea level.

In the most successful cases of filter galleries $\frac{1}{10}$ acre of bottom surface in a gallery has supplied 1000000 gallons per day.

<u>Artesian Wells</u>: I shall only say a word in this paper about artesian wells; a true artesian well is one in which the water rises above the surface of the ground. To show the cause of the flow of water in an artesian well, see the sketch on the next page. The figure hardly needs an explanation; of course the only thing necessary to cause an artesian effect is an impervious strata overlying a water bearing strata in which the water flows under a head. There are a great number of artesian wells all over the world; but it is impossible to tell with any degree of accuracy what the yield will be from an artesian well before it is driven. A thorough geological examination of the country will, however, give

Thesis.




Section Showing the Cause of the Rise of Water in Artesian Wells
In the Basin of London.

some idea of what may be expected.

Artesian wells are often sunk to great depths, and often flow from the ground under a great head. Some wells in Dakota flow under a pressure of 170 pounds to the square inch, and are used to drive machinery.

# Abstract of Thesis.

## The Flow and Yield of Ground-water.

H. C. Daggett '91.
Course I.

The amount of water to be obtained from the ground in any given case, depends upon the extent of tributary water-shed and upon the rainfall over that area. These are, perhaps, the first considerations that an engineer would take into account in making an investigation of the probable yield of ground-water in a given locality. There are, however, other things fully as important to be considered.

The amount of rainfall for any given place is, of course, a variable quantity. Evidently the rainfall to be regarded in estimating the water supply required for a town is the minimum for a series of years, and not the mean.

Records of rainfall over periods of years of considerable length show that the minimum rainfall is about one third less than the mean.

The area of the tributary water-shed is generally defined by the topographical features of the country, but in some cases it may also depend upon the geological structure; as for example, when the rock formation between two water-sheds is fissured and faulty, we shall very often have a flow of ground water through the dividing ridge. The phenomenon has been observed at Malden Mass. When the pumps were started at the driven-well plant in that city, an effect was noticed in the wells of Revere, although it is on the opposite side of a ridge from Malden.

For ordinary soil such as we find in the greater part of New England, the average amount of percolation is from fifteen to twenty percent of the rainfall. Owing to evaporation the percentage is very much less in the summer than in the winter, being often, in this climate, not more than one or two percent of the rainfall during July and August, and occasionally being zero for several consecutive months.

The quantity of water required to saturate any soil depends upon the fineness and kind of material of which it is composed. Coarse gravel will hold from twenty to twenty-five percent of its own volume of water; very fine sand or clay will contain from eight to fifteen percent of its bulk of water; and limestones sandstones and chalk are capable of absorbing from ten to twenty percent of their volume of water. Granites, serpentines, trapeans, gneisses, mica-slates and argillaceous schists are classed as impervious rocks, but may have seams and crevices which gather and lead away, as natural channels, large volumes of water of percolation.

The height of the ground-water, i.e. the height to which the ground is saturated, sometimes called the "water-table", depends upon the uniformity of rainfall, the slope of the ground surface, and the kind of soil.

The slope of the water-table at any time is dependent upon the frequency of rainfall at that time and upon the amount of interstitial friction: By interstitial friction is meant the resistance of the ground to the flow of water through its voids or interstices. In a very wet time the water-table may be at the surface of the ground, even on a hillside; and in a dry time it may fall to the line of no flow, i.e. to point at which the force exerted by gravity, and interstitial friction are balanced. Experiments show that the rate of flow of ground-water under a head of six feet will not exceed two feet per hour. The height and slope of the water-table are influenced by any rivers and streams that flow through the water-shed. To illustrate the difference that may occur in the level and inclination of the water-table it may be mentioned that; in the Sacramento valley the slope is about four feet in a mile, while in the vicinity of Taunton Mass, it is over seventy feet per mile; and that a well has been known to vary seventy feet in two consecutive seasons, when located at some distance from a stream.

If a well be driven below the surface of the ground-water and water be pumped out, the surface of the water-table will take the shape of an inverted cone with its apex at the bottom of the well. The diameter of the base of the cone is estimated to be fifty times the depth of the well, although this varies largely with the amount of interstitial friction; in any case the effect is not great outside of a diameter ten times the depth of the well. The greatest radial effect that has been noticed from a single well, was twelve hundred feet, at a well in Berlin.

The result of long continued pumping from a well is seen at Prospect Park Brooklyn, where continued pumping at an average daily rate of 80400 gallons has permanently lowered the ground-water five feet in eight years.

In cases where a town supply from wells or filter-galleries is under consideration, the conditions of the ground supply must be such as to store up water during the wet part of the year and permit it to be pumped out again in a dry time. At Malden the ground below mean tide is available for storage purposes. The pumps lift water from seventeen feet below mean tide, and allowing for a loss of head of five feet at the pumps and also for the slope of the ground-water it is estimated that an area of 200 acres and an average depth of five feet acts as a reservoir.

Now if we assume the ground

to hold an amount of water equal to ten per cent of its volume, we have a storage capacity of about 50 000 000 gallons.

An important conclusion to be arrived at in discussing the probable yield from ground-water is that no rules can be given, but in any particular case, thorough investigation must be made of all the conditions, and even then the only sure way to find out the supply to be expected is to drive wells and test them.