T H E S I S

THE FLOW OF UNDERGROUND WATER.

June, '02. Phil M.Reilly.

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While the laws governing the flow of water through pipes, channels, rivers, etc. are quite thoroughly understood, very little has been learned or is understood about the flow of underground water, or water through a porous media. There have been several French and German investigators of this subject: in this country Professors F. H. King and C. S. Slichter and Mr. F. H. Newell have been the principal investigators, the latter with the ultimate view of firding out something of the structure and capacity of rocks to furnish petroleum. Professors Slichter and King have worked in conjunction, Professor Slichter investigating the subject from a purely mathematical standpoint and Professor King experimentally, each using the results of the other in his work.

Movements of underground waters may be classed under three heads, viz.; gravitational, thermal and capillary.

Under the head of gravitational movement the most important is seepage, which term is used to express the movement of water through the fine pores of rock or soil under the influence of gravitation. It includes the flow of water in capillary sized channels only. This flow is found to vary with the temperature, a lowering of the barometer causing an increase of flow. This variation of flow due to the temperature, is explained in this way; that the expansion

of the air in the soil above the zone of saturation causes a pressure which increases the hydrostatic pressure due to the difference in level. The settling of the ground would also cause a considerable gravitational flow.

Poiseuille found that water at a temperature of 45 degrees flowed 2.5 times as fast as water at 5 degrees Centigrade, the conditions otherwise being alike.

Thermal movements may be classed as those due to the direct expansion and contraction caused by changes of temperature; and those which are represented by the phenomena of diffusion, osmosis and solution.

Capillary movement takes place away from pore spaces which are wholly or partly filled with water and toward those which are empty or less nearly filled with water than those from which they move. It may proceed in any direction. Conditions such as the pore space and the distance cause a variation in the capillary movement. It has been found that capillary movement is so rapid at four feet that, if the capillary movement was continued throughout the year, it would prevent any part of the rain in the United States from sinking far beneath the surface. Coarse material with large spaces between has the least capillary flow.

When the contour lines of the ground water surface are plotted they show that this surface conforms largely to the surface contour of the ground, showing hills and valleys similar to the earth's surface. This water moves outward from high places in directions nearly the same as superficial water does under like conditions. The water movement would thus be concentrated along the valley lines beneath the surface of the ground.

In investigating the flow of underground waters one of the greatest difficulties met with is that of determining the space through which this underground water flows. If the ground was all homogeneous we might arrive at some definite method, but fissures in the earth, soils of different sized materials and compactness, etc. tend to make this a very variable quantity. Experiments are conducted with

rocks and soils of known, uniform texture and sands of nearly uniform grains.

Several methods have been devised for determining the voids in these different materials. One method is that of direct measurement by micrometer and microscope or other means. Another is that of counting and weighing a known number of grains and then computing the diameter of the mean grain from the number, weight and specific gravity. The third and most accurate method is by means of the aspirator.

As soil, sand, rock, etc. have very small spaces left between the particles, it was supposed that a law closely related to the Poiseuillian-Meyer law for the flow of gases and liquids through capillary tubes,

$$f = \frac{A^2 p}{8 \pi c l}$$

in which A equals the area of cross section,

c " " coefficient of viscosity,

p " " difference in pressure at ends expressed in dynes per square centimeter,

l " " length,

f " " discharge in cubic centimeters per second,

would be found to hold for the flow of liquids through the ground.

The mean velocity of flow through capillary tubes is given by the formula,

$$V = \frac{p A}{8 \pi c l}$$

This last method, by the use of the aspirator, considers Poiseuille's law of capillarity to apply, and the amount of voids that must exist for a measured flow of water or air may be computed. Better results have been obtained by the use of air than by the use of liquids.

It is not enough to know the percentage of volume of empty space in a given medium in order to determine the flow but also the extent of the subdivision and the form of the pore. Professor Slichter has derived the following formula for computing the percentage of pore space;

$$\frac{V\,d - W}{100\,V\,d} = P$$

in which V equals the volume of the vessel in cubic centimeters,

d " " specific gravity of the sand,

W " " weight of sand in grams;

and for computing the effective diameter for grains the following:

$$d^2 = \frac{h}{S\,p\,t}\,(8.9434 - 10)$$

in which d equals the diameter of grain,

h " " length of aspirator, or sand column,

s " " area of the aspirator, or sand column,

p " " pressure in cubic centimeters of water at 20 C.,

t " " time in seconds for 5000 cubic centimeters,

(8.9434 - 10) equals the logarithm of a constant.

He also concludes that the mean effective area of the section of the pore for spherical grains of the same diameter when they have the

closest packing possible, is about 0.1475 times the square of the radius of the grain.

It has been found to be generally true that well-rounded grains of nearly uniform diameter tend to give a pore space which lies between 32 and 40 per cent. Simple sands with angular grains give a much larger pore space than rounded grains. It would, however, seem from experiments that the pore space increases inversely as the diameter, and not to increase in angularity of the grains. This would tend to show that the same laws of flow would hold through a wider range of soil diameters than could be expected if an increasing angularity of the grain occurred with decrease of diameter.

Experiments show that saturated sands and sandstones will hold from 15 to 38 per cent. of their volume of water, and soils and clay from 40 to 50 per cent. Five feet of soil can store two feet of water. Even compact limestones and granite will hold measurable quantities of water.

As would be expected, it is a general rule that the rate of flow of water through rocks is greater along the bedding planes than across them. This fact should be considered in putting down wells; that they should extend down as far as possible into the water-bearing strata so that they will present a greater surface normal to the bedding planes for the water to flow through and not require it to move across the bedding. The increase in depth will also give a greater head.

It has been generally believed that the velocity of the flow of a liquid in a given direction through a column of soil is proportional to the difference in pressure at the ends of the column and inversely proportional to the length of the column. This law is often called "Darcy's Law" and may be expressed by the formula,

$$V = k \frac{P}{h}$$

in which V equals the velocity,

P " " difference in pressure at the ends of the soil column,

h " " length of the column,

k " a constant determined experimentally, depending on the size of soil grains, the porosity of the soil and the viscosity of the liquid.

This law is similar to the Poiseuille law and like it is not true for high pressure gradients.

The results of Newell's experiments showed that the flow of water through sandstone does not conform to the law of Poiseuille between the pressure gradients of 2.3 and 1, and 85 and 1; but increases faster than the pressure. The flow of water through sands was also found not to be proportional to the pressure. The flow of air through sand also increases faster than the pressure. There is a close agreement with the law but the disagreement is all in one direction.

Mr. E. Wollny decided from his experiments that the flow of

water through soils did not follow exactly the capillary law; that the flow increased more rapidly than the increase of pressure.

Using the formula,

$$C = \frac{\log. \left(\frac{p + p_2}{p - p_2} \cdot \frac{p - p_2}{p + p_2}\right)}{p_2 t}$$

in which C equals a constant,

p " the pressure in the reservoir at close of experiment,

p_2 " " constant pressure at the free end,

t " " time,

as employed by Meyer, Hoffman and others, the computed results are too low as compared with the actual measured flow for high pressures.

Mr. King in going over Poiseuille's computations finds that in twenty-three out of twenty-nine tubes used, having lengths greater than one millimeter, the flow increased faster than the pressure. The experiments of Cohen, Röntgen, Warburg and Sachs all give similar results; also that the viscosity decreases faster under high temperatures than it does under low temperatures.

With ten samples of sand the flow was ten per cent. faster in some cases and forty-nine per cent. slower in others than a compliance with the Poiseuille-Meyer law would call for. This series of experiments indicated that with the smaller sizes, where the grains give a minimum pore having diameters 0.0117 mm, 0.0361 mm, 0.0162 mm and 0.181 mm and under, the pressures not exceeding a gradient of three to five, the flow increases faster than the pressure; but where the

diameters of the pores are 0.0276 mm, 0.248 mm, 0.0325 mm, 0.0409 mm and 0.0582 mm the flow does not increase so rapidly as the pressure, even when the gradient is no steeper than one to five. This means that with the larger spaces intervening so many counter currents are set up that the flow is retarded. Taking all these matters into consideration it is found that the Poiseuille-Meyer law as relates to the flow of liquids in capillary tubes is true only within narrow limits, and within still narrower limits for flow through porous media such as soils, rocks, etc.

One point is brought out emphatically by all the observations of these different experimenters; that with either low or high pressures and with long or short columns or tubes the departure from the Poiseuille-Meyer law has been all in one direction; that is, all plus or all minus. This goes to show that it was not errors of observation that caused this departure, but that the law is not strictly true although nearly so.

We know that if a vessel of water is emptied and set down, after standing for a time quite a quantity of water collects in the bottom, due to a film of water that stuck to the sides and did not flow so rapidly as the bulk of the water. On the supposition that under high pressures this film would move faster, this departure might be explained.

Professor Slichter's formula, deduced from mathematical reasoning, viz.;

$$q = (1.0094)\ \frac{p\ d^2\ s}{m\ h\ k} = \text{c.c. per second,}$$

in which q equals the quantity in cubic centimeters,

p is the difference in pressure at the ends of the cylinder in centimeters of water at 4 degrees C.,

d equals the mean diameter of soil grains in centimeters,

s " " area of cross section of the cylinder in square centimeters,

h " " height of the column of sand in centimeters,

m " a constant,

(1.0094) is the logarithm of a factor,

assumes that the flows are proportional to the squares of the diameters. Experiments show that this formula gives very nearly the observed flow.

The observed volumes of water delivered to canals from the surrounding soil is so much greater than the computed flow, considering the soil and rock homogeneous and using the data obtained from the experiments made, that we have to consider that there are underground channels (along fissures, etc.). This is borne out by observations in our mines. The writer has noted in mines that while there seemed to be a general seepage from the rocks, yet along faulting planes or fissures the water ran in streams.

One interesting feature of this problem is the effect on wells in a certain area of lowering the water in an adjacent one. The actual lowering of the ground water surface is more important than the actual interference of one well with another. This also applies to

sub-irrigation; that is the upward movement of the ground water through the soil towards the earth's surface. Two wells 1133 feet apart were experimented with and when water was being pumped out of one well the water in the other well was lowered. The rate of lowering in the well not being pumped, would seem to be accounted for by an actual lowering of the ground water rather than by a change of pressure due simply to a change in the rate of flow, from the fact that the flow of the water was so gradual and continued after the pumping stopped.

The passage of railroad trains near these wells was observed to decrease the lowering; that is, cause more water to flow into both wells, which may have been due to the fact that the jarring of the soil, which would destroy the capillary equilibrium, caused some of the capillary water to become hydrostatic. Or the actual depression of the ground due to the loading and submergance into the ground water surface, caused it to rise beyond the area of this submergance. The fact that a heavy freight train caused a greater effect than a light and more rapidly moving passenger train would seem to show that the latter was the more probable reason.

It is important to note the effect on the capacity of a well of sinking it to different depths into the water-bearing formation. The flow does not increase proportionally to the depth but is relatively more rapid in the shallower wells. This is no doubt due to the reason that in the shallower wells the water has an upper-

tunity to rise upward to the well from below, while in the well which goes to the bottom of the formation, the water must all approach it in parallel planes provided the structure of the different layers is homogeneous. Care must be taken not to puncture the impervious layer at the bottom, else the water may be lost. Where there are layers of different degrees of coarseness penetrated by a well, more water will enter the well from the coarser layers, not only because of the coarser grains but also because the reduction of pressure will be greater and farther reaching in the coarser layers and this will cause the water to flow out of the finer layers into the coarser ones. This shows how the flow into a well may be altered by the position of its bottom: the flow into a well would be increased by going down into a coarser layer instead of stopping in a fine layer and compelling the water to pass from the coarser layer through this finer layer.

Professor Slichter has developed the following formula for the capacity of an artesian well which completely penetrates the water-bearing strata, viz.;

$$f = \frac{2\pi\ h\ (k\ a - k\ a - \ldots\ldots}{\log_e\ (1 - \frac{600}{r}\ \ldots\ldots\ldots)}$$

in which f equals the flow in cubic feet per minute,

h " " amount in feet that the water is lowered by the pump,

r " " radius of the well in feet,

a , a , ...equal the thickness in feet of the various strata

k , k , ... " constants depending upon the transmission capacity of the various strata.

The capacity of a well is not largely influenced by the size of the bore except as the flow is controlled by pipe friction. There would be very little gained in flow by going to the additional expense of putting down a six inch well when a four inch well would carry away all the water supplied by the source.

The flow from a well which does not completely pass through the water-bearing strata is found to be given by a formula similar to the above, but containing the additional term "$2.5\pi k_n h r$" in which k_n is the transmission constant for the bottom stratum.

The writer has been carrying on some experiments to see what could be learned about the underground water here from an investigation of the water in our wells.

In determining the depth to the surface of the water in each well, a point was taken on the curbing or windmill frame and the distance of the surface of the water below this mark was obtained by means of a circular, wooden float one inch thick and one foot in diameter, so fastened to a cloth tape that the disc would remain horizontal when lowered into the well. This was lowered into the well until the float rested upon the surface of the water. The tape was then gradually raised and the difference in tension could be readily noted when the float broke loose from the surface. A spring balance attached to the end of the tape showed a sudden change in tension when the float broke loose. This latter method was used to verify results obtained without the use of the spring balance when they were in any way doubtful. Taking the average of three or four readings and by experimenting with this float in a dish, I found the error in this method would not exceed .02 of a foot.

After these marks had been placed a line of levels and a stadia survey were run and the notes plotted, as shown on map herewith. From this map it would appear that the slope was about one foot in three hundreed feet and to the northeast. This would indicate that the slope was in the general direction of the drainage of the valley and not directly towards the bed of the Santa Cruz. The wells extend

over an area of two thousand by three thousand feet.

These experiments conducted by the writer show that our ground water in this immediate vicinity follows very nearly the contour of the ground, as shown by the profile curves on annexed sheet. These experiments also show that our ground water surface is considerably less than one hundred feet below the surface of the ground.

It would seem as if this entire drainage system, drained by the Santa Cruz on one side and the Rillito, Pantano Wash and Cienega on the other, is a great, slowly-moving river flowing through the ground with swifter moving currents at the lower parts - the river bottoms. If this is so, it would appear to be better for sanitary and economical reasons to seek our city water supply out on the mesa, say up the railroad track.

If this valley is filled with detrital material to a depth of 1500 to 2500 feet, as the geology of the country would indicate, and we find the ground water less than one hundred feet, we would naturally suppose from the nature of this detritus that the remainder of the depth would also be filled with water. This would furnish a great supply of water for lower levels. If these sediments are being gradually compressed at the bottom and cemented together in places by lime, silica, etc., as is no doubt taking place, the water is being gradually forced away from these parts. The consolidation being greatest at the bottom, is forcing the water upwards and if our mountains and rainfall on the mesa do not supply enough to keep the level

at about the same height, this upward movement will help to do so.

There does not seem to be any foundation from the nature of the ground for the statements of residents around here that their wells are fed by special underground streams; but that all our wells draw their supply from this same ground water.

We would expect that this ground water would have a general direction towards our river bottoms. These experiments do not show this to be a fact; but that the water has a general gradient towards the northwest, that is towards the outlet of the valley. These experiments extended of course over a small area. If they are confirmed over a larger area, it would show that our rivers are not rivers flowing underground and carrying water only from their sources as is, I think, the popular opinion; but that they are slightly below the surface of this ground water and are receiving constant additions all along their courses from it.

This is a matter of such recent investigation and one that presents such difficulties to overcome that little success has attended the efforts of investigators as yet. Professor Slichter has recently devised a method, using the electric current, by which the underground flow can be watched and measured. As investigations proceed new methods and apparatus will be discovered, and those who are interested in the matter will continue until they are successful in discovering ways by which the difficulties now existing will be

overcome and they will be able to measure this flow of underground water accurately enough for all practical purposes.

Levelling in Water Determination — Apr. 26, 1902

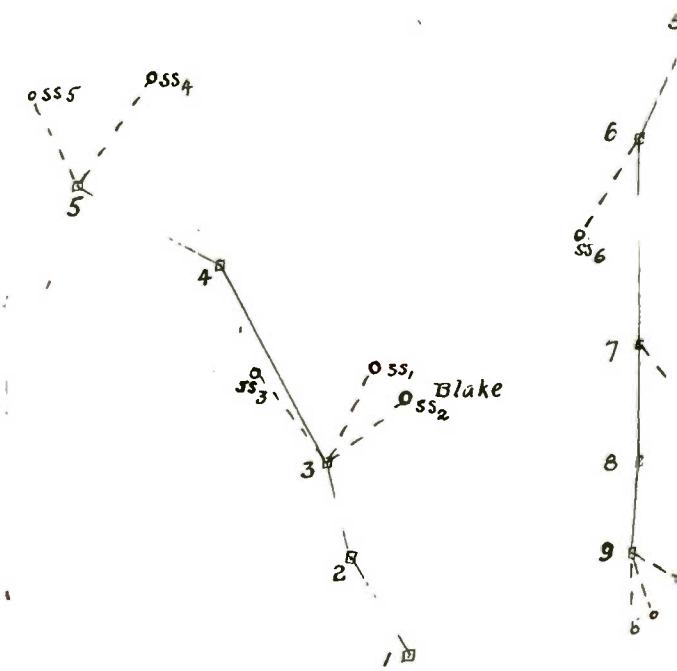
Sta	+S	HI	−S	Elev	Corrected Elev	
	1.24	101.24		100.00	98.68	{Alexander - Inst. Reilly - Rod}
			8.90	92.34	91.02	Well near city monument.
T.P.	8.32	98.30	11.26	89.98	88.66	
T.P.	0.89	94.49	4.70	93.60	92.28	
			3.10	91.39	90.07	Feldman's
			1.83	92.66	91.34	Moore's
T.P.	1.17	94.35	1.31	93.18	91.86	
			3.52	90.83	89.51	Drew's
T.P.	4.81	90.49	8.67	85.68	84.36	
			8.18	82.31	80.99	Barclay's
			4.76	85.73	84.41	
TP	9.58	99.07	1.00	89.49	88.17	
			8.27	90.80	89.48	
			.70	98.37	97.05	

Sta	Brg	Dist	Mg. Brg.	Remarks.
1	00-00	950		
B.S.		680	S58-05W	
11	N71-12E	680	N58-00E	
B.S.		470	S66-00W	
10	N79-04E	470	N66-00E	
"	S77-50E	320	N89-00E	
"	S37-31E	460	S50-30E	
SS	S12-35W	575	S00-30E	

Stadia Survey of 10 Wells near U of A Campus Apr. 26, 1902

Alexander - Inst.
Reilly - Rod

Sta.	Brg.	Dist	Mg. Brg	Remarks.
B.S.		580	N17-05W	
9	S4-05E	580	S17-00E	
B.S.		520	N11-30W	
8	S1-28W	520	S11-30E	
S.S.$_7$	S15-37E	210	S28-30E	
B.S.		565	N16-00W	
7	S3-00E	565	S16-00E	
S.S.$_6$	S26-14W	355	S13-15W	
B.S.		460	N13-00W	
6	S0-7E	465	S13-00E	
"$_5$	N51-22W	485	N64-20W	
S.S.$_4$	N34-29E	390	N21-30E	
B.S.		360	S81-30W	
5	N85-32W	360	N81-30E	
B.S.		450	S48-30E	
4	N35-31W	450	N48-30W	
"$_3$	N47-30W	122	N60-30W	
"$_2$	N88-02W	490	N75-00E	
S.S.$_1$	N52-00E	205	N39-00E	
B.S.		445	S48-00E	
3	N34-54W	445	N47-55W	
B.S.		310	S80-00E	
2	N67-03W	310	N80-00W	
1	0-00	940	N13°-00W	Meridian - N. End.



Name of Party	Distance from mark to surface of water	Distance from mark to surface of ground	Depth of Water Surface from " of ground	Elev. of mark	Elev. of surface of ground
Guild	88.56	3.00	81.75	112.93	110
Blake	84.75	3.00	81.75	106.90	104
	77.71	0.00	77.71	98.82	99
Rogers	78.90	0.50	78.40	97.88	97
Hill	80.85	0.85	80.00	98.68	98
	74.98	1.85	73.13	91.02	89
Moore	69.60	0.00	69.60	91.34	91
Feldman	70.44	0.00	70.44	90.07	90
	58.60	0.50	58.10	84.41	84
Barclay	55.67	3.20	52.47	80.99	78
Drew	64.33	0.25	64.08	89.51	89

(89.00)
16.04
S.S.5

(98.00)
17.73
Barker
S.S.4.

(99.00)
21.11
S.S.1

(97.00)
18.93
Rogers
S.S.3

(104.00)
21.15
Blake
S.S.2

(110.00)
24.37
Guild

(90.00)
19.53
Feldman
S.S.6

Assumed elevation = 100ft.

(91.00)
21.74
Moore
S.S.7

Note.
Levels obtained with Engineer's Level. Horizontal Distances and Bearings determined by Transit and Stadia. Bracketed numbers give approx. ground levels to nearest foot. The other numbers give relative elevations of ground water surface.

(89.00)
25.18
Drew
S.S.10

(84.00)
25.23
S.S.9

S.S.8
(78.00)
25.32
Barclay

MAP

Showing Positions of Wells and Elevation of Standing Water in the vicinity of the

University of Arizona.

May, 1902.

Phi. M. Reilly

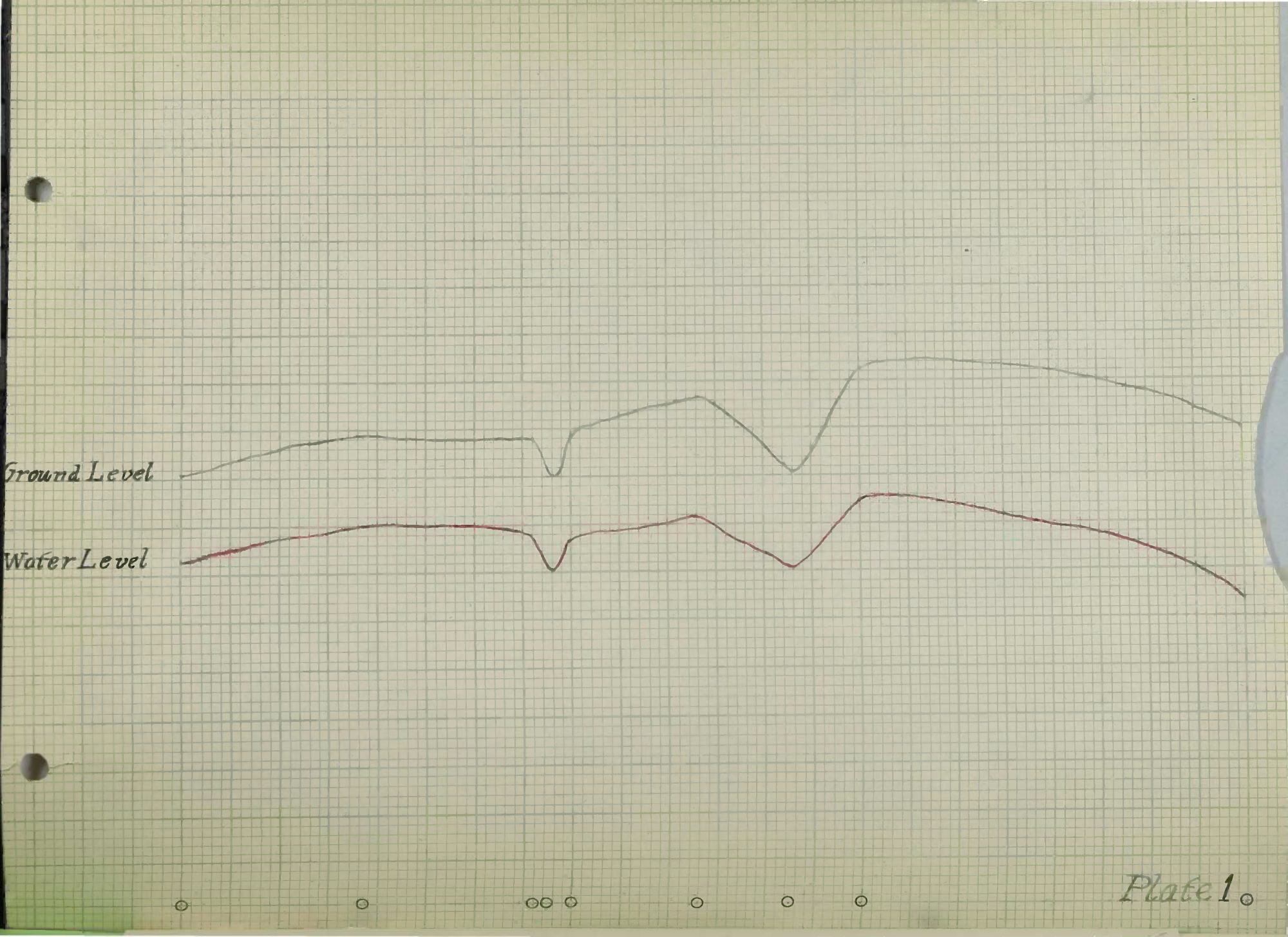


Plate 1.