[4] D. G. Thompson, Report of the Committee on Underground Waters, 1937-38, Trans. Amer. Geophys. Union, 1938, Part I, p. 345.
[5] T. W. Robinson and W. B. Lang, Geology and ground-water conditions of the Pecos River Valley in the vicinity of Laguna Grande de la Sal, New Mexico, with special reference to the salt content of the river water, U. S. Geol. Sur., unpublished report released November, 1938.
[6] G. F. Kay and J. H. Lees, Deep wells of Iowa, Iowa Geol. Sur., v. 33, pp. 231-233, 1928.
[7] The American Ephemeris and Nautical Almanac, Nautical Almanac Office, U. S. Naval Observatory, 1938, pp. 778-793, and 1939, pp. 824-839.

U. S. Geological Survey,
Washington, D. C.

FLUCTUATIONS IN ARTESIAN PRESSURE PRODUCED BY PASSING RAILROAD-TRAINS AS SHOWN IN A WELL ON LONG ISLAND, NEW YORK

C. E. Jacob

(Published with the approval of the Director, U. S. Geological Survey)

Perhaps one of the chief interests of ground-water hydrologists is the study of water-level fluctuations. Since the beginning of the science of hydrology attempts have been made to interpret these phenomena and determine their significance. On the basis of actual observations and "with special reference to Long Island, New York," Veatch [see 1 of "References" at end of paper] in 1906 considered in some detail several different causes of water-level fluctuations. He placed the known causes under two general headings, natural and human. However, considering proximate rather than ultimate causes a further classification might be, and indeed often is, made with regard to the conditions under which the fluctuations are produced by a given agency, natural or human. Thus we speak of "water-table conditions" and "artesian conditions," realizing, however, that the distinction between the two is not always definite. The phenomena peculiar to artesian conditions are usually the result merely of the imperviousness of the confining beds relative to the particular aquifer under consideration. Indeed, it is recognized that perhaps even the most dense clay is not absolutely impervious to the flow of water, given a difference in head, sufficient to produce the flow, though it may be beyond the precision of the means now employed to detect the flow of water through such impervious strata.

In general, water-level fluctuations observed under artesian conditions may be divided into two groups, those occurring while the load on the aquifer remains constant and which are due to various other causes, and those resulting from actual variations in the load on the aquifer. In the first group are those fluctuations caused by variations in the head in areas of recharge or discharge and those caused by pumping from wells.

Variations in the load on artesian aquifers may be comparatively wide-spread in some cases and subject to varying degrees of restriction in others. Thus the second group mentioned above includes fluctuations of varying magnitude and duration depending on the extent, intensity, and rate of variation of the load. Perhaps the best example of a wide-spread and uniform load which is subject to more or less periodic variation is the atmospheric pressure. Variations in atmospheric pressure produce so-called "barometric fluctuations."

Fluctuations are produced by more restricted loading arising from such natural agencies as erosion and deposition and from variations in the level of streams, lakes, or other bodies of water overlying artesian aquifers, and also from such human agencies as buildings and other structures, and, lastly, railroad-trains. Thus, according to the classification proposed here this paper is concerned primarily with fluctuations produced under artesian conditions by a particular type of restricted variable load.

In the work of King [2] referred to by Veatch [1] is a description of water-level fluctuations produced by freight-trains passing a six-inch well which was about 140 feet from the railroad at Madison, Wisconsin. This is doubtless the earliest mention of this phenomenon appearing in American scientific literature. The well in question was 40 feet deep and penetrated three feet of sandstone which was presumably overlain by 37 feet of unconsolidated material. As a loaded freight-train slowly passed the well there was produced "a rapid but gradual rise of the water, . . . followed by only a slightly less rapid fall to the normal level." Veatch remarks that "it is not clear that the water is under artesian head." However, it is now generally conceded that artesian conditions are necessary to produce fluctuations of the type and magnitude observed here.

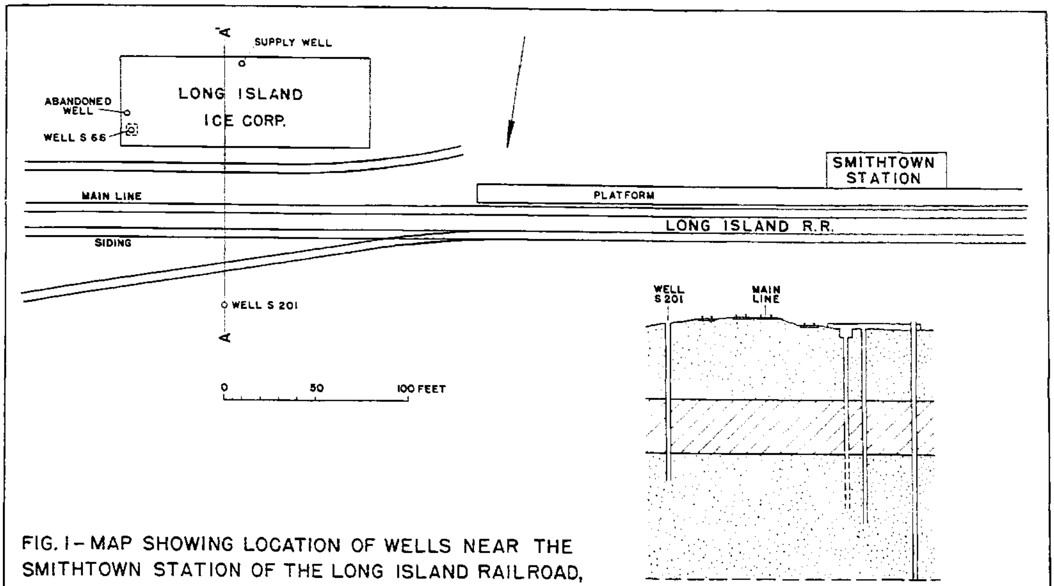

FIG. 1 - MAP SHOWING LOCATION OF WELLS NEAR THE SMITHTOWN STATION OF THE LONG ISLAND RAILROAD, AND SECTION PERPENDICULAR TO THE TRACKS

SECTION A-A'

Observations were begun on an abandoned well of the Long Island Railroad on April 15, 1937. This well, known as Well S-201, is located 54 feet north of the main line of the Port Jefferson branch of the Long Island Railroad and about 360 feet east of the Smithtown Station, as shown on the map in Figure 1. It is eight inches in diameter at the surface and is 89 feet deep. The water-level is 35 to 40 feet below the surface. Unfortunately the log of the well is not available. Information regarding the area and position of the screen is also lacking. However, there is available the log of a nearby abandoned well, Well S-66, which is 110 feet to the southeast of Well S-201 and is on the property of the Long Island Ice Corporation on the opposite side of the tracks. The log [3] of this well as given by the driller, Mr. Emil Lorentson, is as follows:

Material	Thickness in feet	Depth in feet
Sand, fine, brown	40	40
Clay, brownish	30	70
Gravel	30	100

The section shown in Figure 1 is based on this log. According to the statement of the driller the same general conditions were encountered in other wells drilled in the vicinity of Smithtown. The thickness of the gravel underlying the clay is not definitely known, nor is the extent of the confining layer. This is the Gardiners clay, which is generally quite extensive on Long Island but which is lacking in some places owing to erosion which took place prior to the deposition of the overlying material. The fact that the water-level in Well S-201 fluctuates in response to variations in atmospheric pressure indicates that at least in the immediate vicinity of the well the confining layer is continuous. However, the low "barometric efficiency" of this well, to be considered presently, indicates that at a point some distance from the well the confining layer may be absent.

In addition to Well S-66 there are two other wells on the property of the Long Island Ice Corporation, one of which is abandoned and the other is used as a supply-well and for cooling purposes in the manufacture of ice. The supply-well is reported to be ten inches in diameter and 142 feet deep with a 20-foot strainer between 122 and 142 feet. It is equipped with a multi-stage turbine-pump with a capacity of 300 gallons a minute.

On April 15, 1937, a Stevens "Type-F" water-stage recorder was installed on Well S-201 with a seven-inch float. Since then, except for occasional short interruptions when intensive studies were being made, this instrument has been in continuous operation on a weekly basis with a natural gage-height scale. This recorder is of the conventional horizontal-drum type, in which the drum is rotated by a float attached to a flexible beaded cable which passes over a grooved

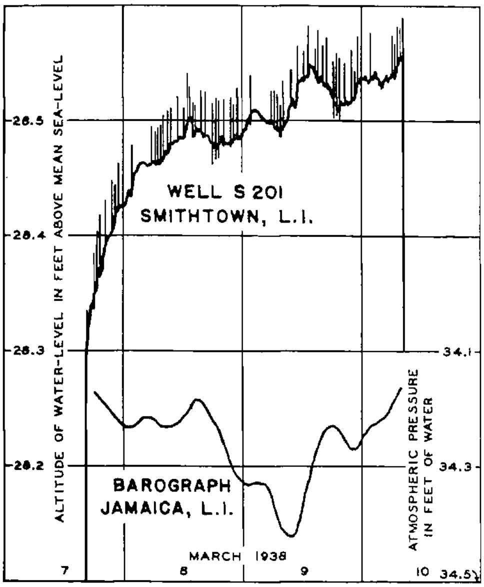

FIG. 2—INSTRUMENTAL RECORD OF WATER-LEVEL IN WELL S-201 AND BAROGRAPH FOR MARCH 7-10, 1938

wheel or pulley geared to the drum. The drum on this recorder is one foot in circumference. The chart is 9.6 inches wide. When the instrument is operated as a weekly recorder, the time-scale is 1.2 inches to the day.

The weekly recorder-charts taken from the instrument on Well S-201 are interesting in that they show three or more types of water-level fluctuations. The most prominent fluctuations shown on the charts are due to pumping from the supply-well, which is about 134 feet away. There are produced a series of the familiar "drawdown-curves" and "recovery-curves" corresponding to successive pumping and non-pumping periods. The total drawdown produced in Well S-201 after eight hours pumping of the supply-well is about 1.0 foot. The curve shown in Figure 2 is a reproduction of the instrumental record from about 4:00 p.m., March 7, to about 10:00 a.m., March 10, 1938. The pump on the supply-well 134 feet away was shut down at about 4:00 p.m., March 7. As a result the water-level in Well S-201 recovered, rapidly at first and then more gradually. At about 10:00 a.m., March 10, pumping was resumed, whereupon the water-level declined.

Superimposed upon the fluctuations due to pumping are those produced by the passing railroad-trains. These fluctuations are of such small magnitude and of such short duration, however, that they appear merely as vertical lines on the chart, and when the water-level is rising or falling quite rapidly in response to pumpage they are often obliterated. In addition there are fluctuations of longer period due to variations in atmospheric pressure as seen by comparing the record from the water-stage recorder with the barograph-record which is plotted on an inverted scale below the water-level curve. By comparing the instrumental record for the period October 22 to November 19, 1938, with the inverted barograph for the same period, it was found that the "barometric efficiency" of Well S-201 is about 20 per cent, that is, the water-level in the well rises 0.2 foot in response to a drop in atmospheric pressure equivalent to a head of one foot of water.

Except where there is a simultaneous fluctuation due to some other cause, such as pumping, it is possible, from the known times of arrival and departure of the various trains, to check each train and determine the magnitude of the fluctuation which it produces. From a study of the recorder-record for March 8, 9, 11, 15, and 18, 1938, it was found that the west-bound trains produced fluctuations ranging from 0.024 to 0.035 foot and averaging 0.030 foot, whereas the east-bound trains produced fluctuations ranging from 0.036 to 0.054 foot and averaging 0.045 foot. Other things being equal, the magnitude of the water-level fluctuations should depend on the weight and the velocity of the trains passing the well. As far as is known, except perhaps on special occasions, the trains have from three to eight coaches each. Two types of locomotives are used on the passenger-trains, one weighing about 237,000 pounds and the other about 309,000 pounds including coal and water. The passenger-coaches average in weight about 110,000 pounds. Each week-day there are 11 east-bound and 11 west-bound trains. Inasmuch as each east-bound train returns within a few hours as a west-bound train, the average weights of east-bound and west-bound trains must be equal over a period of one day or a number of days. This being the case, the observed differences in average water-level fluctuations--0.045 foot for the east-bound and 0.030 foot for the west-bound trains--may be ascribed to differences in the average velocity of the respective trains.

According to observations made April 23, 1937, it is estimated that the east-bound trains pass the well with an average velocity of about 20 feet a second, whereas the west-bound trains have a velocity of 40 or 50 feet a second as they pass the well. The station-platform is a few hundred feet to the west of the well. Thus, west-bound trains may pass the well before appreciably decreasing their speed, whereas east-bound trains doubtless pass the well before attaining their normal speed.

There is apparently a certain velocity at which a train of a given length and weight will produce the greatest fluctuation. If the train passes the well at a lower velocity, the confined

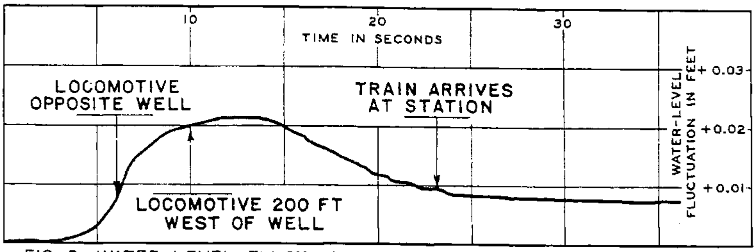

FIG. 3—WATER-LEVEL FLUCTUATION IN WELL S-201 PRODUCED BY WESTBOUND TRAIN, 12^h12^m P.M., APRIL 23, 1937

water is given more time to escape laterally and thus dissipate the pressure before it is built up to its full value. On the other hand, if the train passes the well at a higher velocity, the strata overlying the aquifer are not given as much time to become adjusted to the varying load at the surface. Consequently, the load is distributed over a wider area and the intensity of the increased load on the aquifer is less.

Well S-66 is clogged and it is therefore unlikely that it responds to the passing trains. However, it was found that the other abandoned well on the property of the Long Island Ice Corporation does exhibit fluctuations due to the passing trains. This well is eight inches in diameter and sounds 112 feet deep. On March 23, 1938, a Stevens "Type-F" recorder was installed with a seven-inch float and a 1 to 1 gage-height ratio. It was operated on a weekly basis until April 20, 1938. The fluctuations produced by the passing railroad-trains are apparent on the weekly recorder-charts, but they are of much smaller magnitude than those observed in Well S-201. From a study of the instrumental record for April 12, 1938, it was found that nine east-bound trains produced average fluctuations of 0.006 foot and that nine west-bound trains produced average fluctuations of only 0.004 foot. The same trains produced in Well S-201 average fluctuations of 0.046 and 0.030 foot, respectively. Well S-201 is 54 feet from the center-line of the tracks. The 112-foot well is 52 feet from the center-line and on the opposite side of the tracks. When use of this well was discontinued some time ago, the pump-cylinder and check-valve were left in it. This accounts for the sevenfold or eightfold reduction in the magnitude of the water-level fluctuations produced by the passing trains.

More detailed observations of the effect of passing railroad-trains on the water-level in the Smithtown well were begun April 23, 1937, by M. L. Brashears and the writer. In order to magnify the water-level fluctuations in Well S-201 the regular float-wheel was replaced by a special wooden pulley about 1-1/8 inches in diameter giving a gage-height ratio of about 5.1 to 1. And in order to enlarge the time-scale so that the fluctuations might more easily be studied the clock on the recorder was replaced by a special clock which gave a time-scale of about five seconds to the inch. As the recorder-chart was only 9.6 inches long, the maximum continuous time of travel of the pen was only about 48 seconds. If additional record was desired, it was necessary to rewind the pen-carriage cable. About 30 seconds time was required for this operation.

On April 23 observations were made on three west-bound and two east-bound trains. The curve shown in Figure 3 is a reproduction of the first part of the instrumental record obtained during the arrival and departure of the 12:12 p.m. west-bound train, which consisted of a locomotive and three coaches. Data regarding the position of this train at various intervals of time are given in Table 1.

It is seen from Figure 3 that as the train approached from the east the effect did not become appreciable until the locomotive was within 100 or 200 feet of the well. As the locomotive

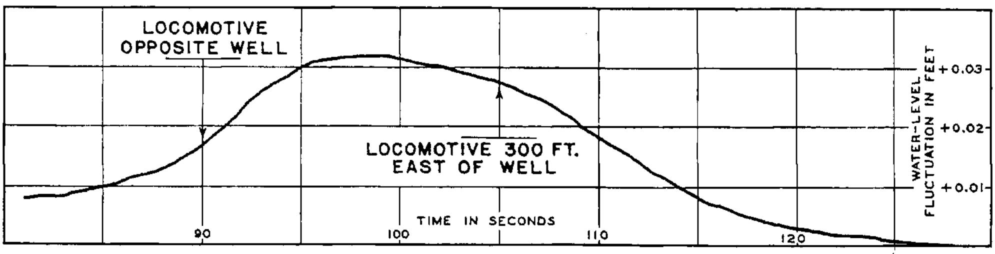

FIG. 4—WATER-LEVEL FLUCTUATION IN WELL S-201 PRODUCED BY EASTBOUND TRAIN, 1^h04^m P.M., APRIL 23, 1937

Table 1--Data regarding west-bound train, April 23, 1937

Time elapsed	Notes
seconds	
0	Record begun; locomotive 300 feet east of well
6	Locomotive opposite well
10	Locomotive 200 feet west of well
23	Train arrived at station
36	Record interrupted (to rewind pen-carriage cable)
70	Record continued
85	Train departed from station
95	Record ended

passed the well the rise became quite abrupt. The water-level reached a maximum shortly after the approximate center of gravity of the train passed the well. (The train was about 300 feet in length and passed the well with an estimated velocity of 50 feet a second.) The decline in the water-level as the train arrived at the station and stood opposite the platform was more gradual than the rise produced by the same train as it approached and passed the well. No additional fluctuation occurred as the train left the station, the second part of the curve being merely a continuation of the first part.

The curve given in Figure 4 is a reproduction of the second part of the record obtained during the passage of the 1:04 p.m. east-bound train after the pen-carriage cable had been rewound. Observations on the position of this train, which consisted of a locomotive and four cars, are given in Table 2.

Table 2--Data regarding east-bound train, April 23, 1937

Time elapsed	Notes
Seconds	
0	Record begun
42	Record interrupted
46	Train arrived at station
75	Train departed from station
81	Record continued (after rewinding pen-carriage cable)
90	Locomotive opposite well
105	Locomotive 300 feet east of well
128	Record ended

As the train approached the well from the west, after leaving the station, the rate of rise of the water-level increased continuously and reached a maximum shortly after the locomotive passed the well. The water-level reached its maximum height about 99 seconds after the beginning of the record. The decline in the water-level as the train continued eastward beyond the well was more gradual than the preceding rise. As seen by comparing Figures 3 and 4, both the rate of rise and the rate of decline were less for the east-bound train than for the west-bound train. However, the magnitude of fluctuation produced by the east-bound train was greater than that produced by the west-bound train. These differences are ascribed mainly to the difference in the velocity of the two trains, as previously discussed.

Observations were resumed in March, 1938, the water-stage recorder having been maintained in continuous operation on a weekly basis during the interim. In the series of observations which followed a second special clock was used which moved the recording pen eight inches in 30 minutes. This was a spring-driven clock similar to the type with which the recorder was originally equipped, but which had been converted into a weight-driven clock. Using this clock and the special float pulley described above, observations were made on regularly scheduled east-bound and west-bound passenger-trains as well as on three freight-trains.

Of particular interest is the graph shown in Figure 5 which shows the fluctuations in water-level produced by a passing freight-train on March 21, 1938. This was an east-bound freight consisting of a locomotive, 19 cars, and a caboose. Observations on the position of the train at various intervals of time are given in Table 3.

Assuming the average length of freight-car to be 42 feet, the total length of the train was about 900 feet. It was not possible to ascertain the exact weight of the train. However, it is known that the average weight of freight-cars when empty is about 45,000 pounds and that the

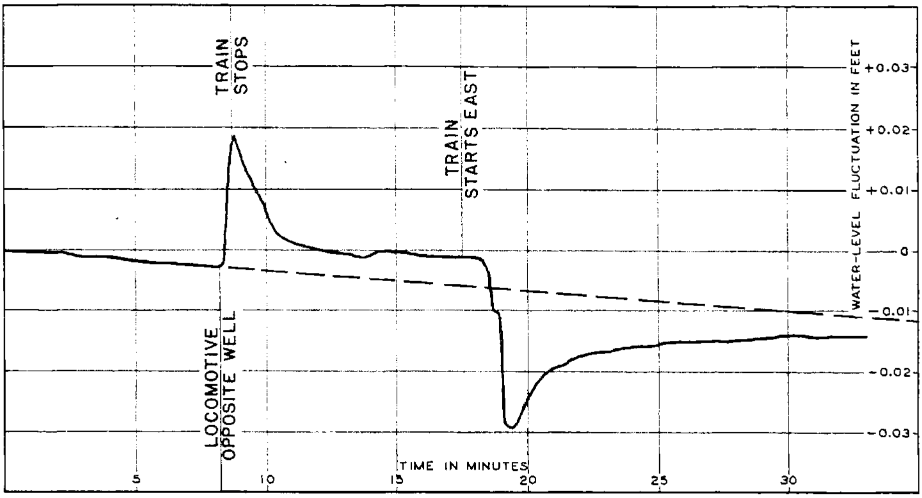

FIG. 5—WATER-LEVEL FLUCTUATION IN WELL S-201 PRODUCED BY EASTBOUND FREIGHT TRAIN, MARCH 21, 1938

Table 3--Data regarding east-bound train, March 31, 1938

Elapsed time m	sec	Notes
0	0	Record begun (3:04 p.m.)
8	10	Locomotive opposite east end of platform
8	15	Locomotive opposite well
8	45	Train stopped, locomotive and 8 cars to east of well
9	15	Locomotive and four cars detached from front end of train; one car switched to siding
13	45	Locomotive and three cars recoupled to train
17	30	Train started east
18	45	Caboose at switch
33	00	Record ended

locomotive, of type 2-8-0, weighs about 250,000 pounds. Thus the total weight of train when empty would be about 1,150,000 pounds, or about 1280 pounds for each foot of length. Not infrequently the live-load on freight-trains exceeds twice the dead-load. It seems reasonable, therefore, to assume that in this case the live-load at least equalled the dead-load. Thus the weight of loaded train was possibly 2500 pounds for each foot of length.

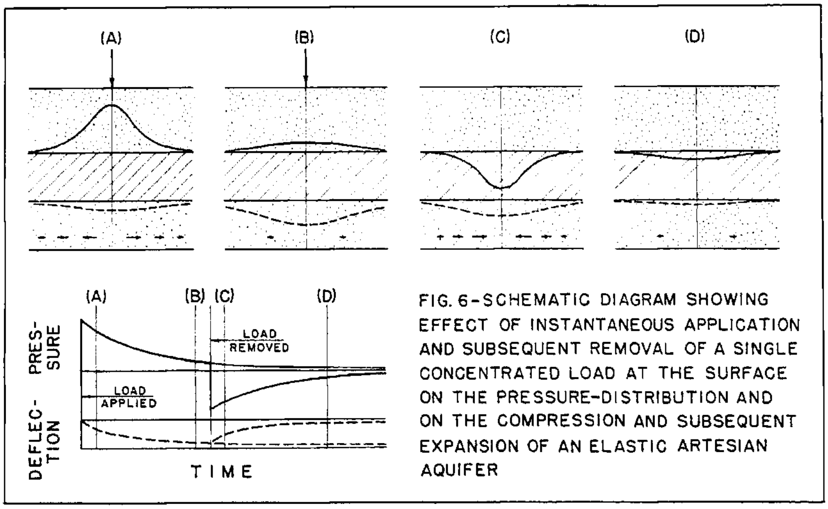

FIG. 6-SCHEMATIC DIAGRAM SHOWING EFFECT OF INSTANTANEOUS APPLICATION AND SUBSEQUENT REMOVAL OF A SINGLE CONCENTRATED LOAD AT THE SURFACE ON THE PRESSURE-DISTRIBUTION AND ON THE COMPRESSION AND SUBSEQUENT EXPANSION OF AN ELASTIC ARTESIAN AQUIFER

As indicated by the initial rate of decline of the curve in Figure 5, the water-level fluctuations produced by the passing freight-train are superimposed on a general downward trend of the magnitude of about 0.02 foot an hour. As the train approached from the west no appreciable effect was observed until the locomotive was nearly opposite the well, whereupon the water-level rose quite abruptly, reaching a maximum of 0.022 foot in about 30 seconds. The maximum occurred shortly after the train had stopped, the locomotive and eight cars then being to the east of the well. Thereafter the water-level gradually declined. In the meantime the locomotive and four cars were "cut" from the front of the train and one of the cars was switched to the siding on the opposite side of the tracks. As the locomotive and the three cars were recoupled to the train a slight rise occurred in the water-level.

The train started east 17 minutes and 30 seconds after the beginning of the instrumental record. As the train left the vicinity of the well a decline in water-level occurred which was comparable both in magnitude and in duration to the rise produced as the same train arrived opposite the well. The rate of decline of the water-level did not become appreciable until nearly all of the train had passed the well. Indeed the maximum rate of decline occurred after the caboose passed the switch 350 feet east of the well. The water-level reached a minimum of 0.023 foot, that is, 0.023 foot below the broken line in Figure 5. Subsequently the water-level recovered, rapidly at first and then more gradually, and approached the level which it otherwise might have had, as indicated on the diagram by the broken line, which is a continuation of the general trend of the water-level in the well before the arrival of the train.

In order to visualize more clearly the effect of the freight-train, the moving load of the train may be considered to be replaced by a load equivalent in lateral extent, which is fixed in position opposite the well, and which varies in magnitude in such a manner as to produce the same effect in the well as that actually produced by the train. This procedure seems justifiable in view of the fact that the time that elapsed between the first noticeable effect as the train approached the well and the stopping of the train opposite the well was small compared to the rate of demise of the pressure-disturbance produced by the train. To simplify matters further, this varying distributed load may be replaced by a single concentrated load which is applied instantaneously, maintained at a constant value for a period of time, and then removed instantaneously.

The diagrams in Figure 6 are intended to indicate, schematically at least, the effect of such a load on the pressure-distribution within an elastic artesian aquifer and on the compression and subsequent expansion of the aquifer following removal of the load. The diagrams A, B, C, and D show the distribution of pressure and the deflection of the upper surface of the aquifer at the respective times indicated on the time-pressure and time-deflection curves. The hydrostatic pressure in the aquifer is plotted as a full line, the upper limit of the confining layer arbitrarily being adopted as a base. The deflection-curve for the upper surface of the aquifer is plotted as a dashed line. (The lower surface of the aquifer is assumed fixed.) These quantities are, of course, grossly exaggerated and are obviously plotted to quite different scales. The lengths of the arrows indicate the relative magnitude of the velocity of flow at various distances from the load. The lower diagram in Figure 6 shows, by the heavy full line, the change in pressure produced by the load, and, by the heavy dashed line, the deflection of the upper surface of the aquifer, plotted against time.

Inasmuch as the load is applied instantaneously, the initial adjustment in the fraction of the load borne by the confined water and that borne by the solid material of the aquifer may also be considered to occur instantaneously. As a result the hydrostatic pressure rises instantaneously to its maximum value at any point a given distance from the load. Thereafter, the pressure declines, as indicated by the time-pressure curve in Figure 6. If the load were maintained further, the pressure would approach asymptotically its original value as indicated by the continuation of the first limb of the time-pressure curve. However, as the load is removed a second instantaneous adjustment takes place as a result of which the pressure drops to a minimum. The drop in pressure is theoretically equal to the initial increase in pressure. Following removal of the load the pressure recovers and tends towards its initial value, somewhat in accordance with the second limb of the time-pressure curve in Figure 6.

The time-deflection curve in Figure 6 shows the manner in which the aquifer is compressed by the load and subsequently expands following removal of the load. The rate at which compression or expansion proceeds at a point a given distance from the load is in general proportional, though not necessarily directly so, to the difference between the actual pressure at that point and the normal or initial pressure. Thus the rate of compression is initially maximal, as indicated by the slope of the time-deflection curve. As compression of the aquifer continues, the rate of compression becomes continually smaller. The first limb of the time-deflection curve approaches asymptotically the value of deflection determined by the magnitude of the load and by the elasticity of the solid material.

Initially the increase in load is shared by the confined water and by the solid material of the aquifer in accordance with their respective moduli of elasticity and depending on the porosity of the material. However, as the water flows radially away from the point of application of the load in response to the temporary gradient, a continually increasing proportion of the load is borne by the solid material. Ultimately, all of the increase in load is borne by the solid material of the aquifer, the hydrostatic pressure having been restored to its initial value.

Upon instantaneous removal of the load the aquifer expands, the initial rate of expansion being maximal. As the aquifer is assumed to be perfectly elastic, it ultimately returns to its original shape.

A comparison of the curve shown in Figure 5 with the theoretical time-pressure curve in Figure 6 indicates quite definitely that at least for the range of pressures involved the elasticity of the particular aquifer in question is reasonably perfect. Although not based on actual calculations, the theoretical curve is believed to be consistent with the assumptions made. And to the extent that these assumptions are met by the actual conditions the conclusion derived therefrom is believed to be sound.

In studying water-level fluctuations observed in artesian wells there frequently arise questions regarding the faithfulness with which the head in the well represents the pressure in the formation. And when such wells are equipped with automatic water-stage recorders there arise further questions with regard to the validity of the instrumental record as a reproduction of the fluctuations which occur in the well. These questions deserve consideration in connection with the record of Well S-201.

Obviously, unless a well is entirely shut off from the formation, under static conditions, at least, the head inside and outside the well should balance. And under such conditions an instrument should record the true position of the water-surface. However, the moment fluctuations in hydrostatic pressure occur in the aquifer the inertia and friction of the system and of the recording mechanism enter into the picture. Furthermore, there is to be considered the volume of water entering or leaving the well as the water-level rises or declines and consequently also the head required to move the water through the well-screen and radially through the formation toward or away from the well, as the case may be. It is merely a question of the relative magnitude of these effects and the particular fluctuation under observation.

The additional force required to overcome the frictional and inertial resistance of the recorder-mechanism causes the float to "lag" whenever there is a change in the water-level in the well. That is, if the stage is rising, the float is submerged more than usual, the increased displacement giving rise to the required additional force. On the other hand, if the stage is falling, the float is submerged less than usual. The difference between the position of the float relative to the water-surface at a given instant when the water-surface is in motion and its position relative to a static water-surface is spoken of as the "float-lag."

As there is reason to believe that, because of the nature of the bearings, the frictional moment is not wholly independent of the velocity of rotation of the drum as ordinarily assumed but is comparatively small for extremely low rational velocities, the lag during slow movements is doubtless negligible. Accordingly fluctuations occurring in artesian wells due to such causes as variations in atmospheric pressure and pumping from wells some distance away generally are faithfully reproduced by a recorder unless the bearings on the shaft of the drum are in rather poor condition. When the friction of the bearings is sufficient to cause an appreciable "float-lag," the same will be apparent, producing "steps" in the curve on the weekly recorder-chart. However, when rapid fluctuations in pressure occur, such as are produced by passing railroad-trains, the lag may be appreciable without leaving any such evidence of its presence. This is true with regard to records obtained using either of the special clocks as well as the usual weekly records.

It is evident that by changing the diameter of float-wheel on a given recorder the effect of the float-lag may be changed. For, given the diameter of the float and the vertical acceleration of the water-surface in the well, and assuming a constant frictional amount (independent of the angular velocity of the drum), the float-lag due to friction in the bearings on the shaft is inversely proportional to the diameter of the float-wheel. The float-lag due to inertia of the drum, shaft, and gears, neglecting the inertia of the float-wheel itself, is inversely proportional to the square of the diameter of the float-wheel. Thus any advantage gained by using a smaller float-wheel to increase the gage-height ratio is partly lost because of the accompanying increase in float-lag.

This was evident from a study of the curves for the nine west-bound trains on which detailed observations were made. When a small float-wheel was used, giving a gage-height ratio of 5.1 to 1, the trains produced an average fluctuation on the charts of only 0.019 foot. This is only about 63 per cent of the average fluctuation of 0.030 foot recorded on the weekly charts when the regular 1 to 1 gage-height ratio was used. However, in the case of the east-bound trains no such difference was found. The curves for the four east-bound trains obtained with the smaller float-wheel indicate that the magnitude of fluctuation on the charts produced by those trains averages 0.045 foot. This happens to be equal to the average fluctuation as recorded on the weekly charts.

The agreement obtained here is doubtless in part accidental owing to the paucity of the data. However, it is evident that with a given diameter of float-wheel the inertial lag is approximately proportional to the vertical acceleration of the water-surface in the well, whereas the frictional lag is supposedly independent of the angular acceleration of the drum and hence also of the vertical acceleration of the water-surface. Hence for small values of vertical acceleration the inertial lag may be quite small in comparison with the frictional lag regardless of the size of the float-wheel. However, for large values of vertical acceleration the inertial lag may be appreciable in comparison with the frictional lag, and, being inversely proportional to the square of the diameter of the float-wheel, is proportionately larger in the case of the smaller float-wheel, the frictional lag being inversely proportional to the first power of the diameter of the float-wheel.

It is seen, by comparing Figures 3 and 4, for example, that the maximum vertical acceleration, as indicated approximately by the curvature of the respective curves, is several times greater in the case of west-bound trains than in the case of east-bound trains, though the magnitude of the fluctuation is actually greater in the latter case. Moreover, it should be remembered that the curve shown in Figure 4 is probably a reasonable reproduction of the actual fluctuation because in that case the float-lag is small, whereas the curve in Figure 3 represents the actual fluctuation appreciably diminished because of lag. Hence a comparison of the actual fluctuations in the two cases would show a still greater difference in acceleration.

No attempt will be made at this writing to evaluate the stresses produced in the aquifer, except to state that such evaluation is theoretically possible. The problem of determining the distribution of stress produced in an isotropic semi-infinite body by a concentrated load acting normal to the surface was solved by Boussinesq [4]. By means of superposition this solution may be extended to non-uniform distributed loads. And, except as limited by the means at our disposal, it should be possible from the known distribution of stress within the aquifer to determine the accompanying increase in hydrostatic pressure and the variation of the same with distance from the applied load and with time as the water moves in response to unbalanced pressures. Actually the problem is beset with serious difficulties owing particularly to the successive discontinuities between the various strata. However, it appears that these difficulties may, in a measure at least, be overcome by resorting to certain simplifying assumptions.

References

[1] A. C. Veatch, Fluctuations of the water level in wells with special reference to Long Island, New York, U. S. Geol. Sur. Water-Supply Paper 155, 83 pp., 1906.

[2] F. H. King, Bull. U. S. Weath. Bur. No. 5, pp. 67-68, 1892.

[3] Record of wells in Suffolk County, N. Y., New York State Water Power and Control Commission, Bull. GW-4, p. 49, Albany, 1938.

[4] J. Boussinesq, Application des Potentiels . . ., Paris, 1885; see also S. Timoshenko, Theory of elasticity, McGraw-Hill, pp. 328-338, 1934.

U. S. Geological Survey,
Jamaica, New York

DISCUSSION OF QUESTION NO. 2 OF THE INTERNATIONAL COMMISSION ON SUBTERRANEAN WATER: DEFINITIONS OF THE DIFFERENT KINDS OF SUBTERRANEAN WATER

O. E. Meinzer

The hydrologists who are concerned with the study of the water that occurs below the land-surface feel strongly the need of better agreement among the different countries as to the funda-