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MEASUREMENT OF EFFECTIVE FLOW VELOCITY OF GROUND WATER BY MEANS OF DISSOLVED GASES

RYUICHI SUGISAKI

Institute of Earth Sciences, Nagoya University, Nagoya, Japan

ABSTRACT. Confined ground water is isolated from the air, and its content of dissolved gases is decisively controlled by the temperature of the water when it was exposed to the atmosphere. On account of seasonal variation of the original water temperature, there must be seasonal variation in the dissolved-gas content of ground water. The gas content as influenced by seasonal variation of temperature has been investigated by successive observations of water from a few wells and by simultaneous measurement of water from many wells. The time when water soaked into the ground can be inferred for each sample from the variation of dissolved-gas content, and the effective velocity of ground water can be calculated thereby. The effective velocity observed in an aquifer consisting of coarse gravel ranges from 3.6 to 10 meters per day, corresponding to different hydraulic gradients. If these values are converted by Darcy's formula into the velocity along a one percent hydraulic gradient, they range from 36 to 58 meters per day.

INTRODUCTION

In order to estimate the water-supplying ability of a well and of an aquifer, it is necessary to determine the coefficient of permeability in a stratum. There are several methods for determining the coefficient of permeability. One of these is to calculate it from the effective velocity of ground water in the field.

The earliest method used for measuring the velocity of ground water movement was that of Thiem (1887), who introduced sodium chloride in an upstream well and tested samples taken from a downstream well. The mean velocity was determined by the time elapsed until the highest chloride concentration occurred in the downstream well. Slichter (1905, p. 16-28) developed the method by using other electrolytes, and measured electrometrically. The conductivity of water is increased by the addition of an electrolyte; the variation of concentration of introduced ammonium chloride was electrically measured. Dyes such as uranin have also been used instead of salts. All these methods are widely used in the field. However, there are doubts about them: (1) When an appreciable amount of salt or dye solution is introduced in a well, the water level rises, increasing the inclination of the water table. (2) Dyes may sometimes be decomposed or absorbed by organic matter in the ground. (3) The salt or dye does not appear abruptly in the downstream well, but its appearance is gradual and irregular; it is difficult to determine the arrival time of the tracer.

It is therefore desirable to make use of natural tracers, which do not disturb the ground water table.

Grosse and others (1951) discovered the natural occurrence of tritium (half-life 12.5 yr) produced by cosmic rays. Libby (1959) measured the tritium content of water from selected wells in Nebraska and discussed its hydrologic application. Beryllium-7 produced by cosmic rays was also found in rainwater by Arnold and Al-Salih (1955). The half-life of Be^7 is only 53 days, and it would not be applicable to the study of ground water movement.

Oana (1954) suggested that it is feasible to deduce the time when water soaked into the ground by measuring the argon content of ground water. When water flows on the Earth's surface in contact with atmospheric air, its content of dissolved gases is determined by its temperature. The temperature of surface water varies seasonally, with a maximum in summer and a minimum in winter, and the content of dissolved gases therefore has a minimum in summer and a maximum in winter. When water soaks into a confined aquifer, its content of dissolved gases is expected to reflect the annual cycle of atmospheric

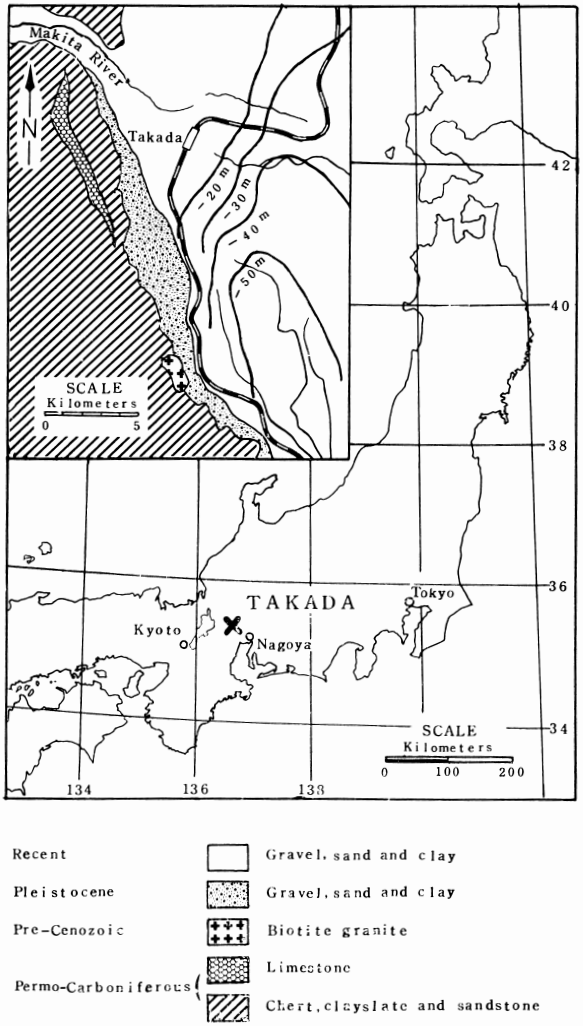

Fig. 1. Index map with geologic map of part of Nagoya District, based on 1:200,000 map published by the Geological Survey of Japan, 1955. On the geologic map, contour lines show the upper boundary of a gravel bed, the aquifer studied in this paper. Altitudes in meters below sealevel.

temperature. The content of dissolved gases as observed in the ground water is more or less smoothed, probably because of gas diffusion and mixing of water. However, where the difference in water temperature between winter and summer is considerable, the variation of dissolved-gas content can be detected in ground water. When the content of dissolved gases in water taken from the same well is successively measured, revealing its maximum and minimum in a year, we can deduce the time of year during which each sample entered the ground. Oana pointed to the usefulness of argon as a tracer for this purpose; argon is inert and never undergoes any chemical reaction in the ground. Oana (1954, 1957) measured successive variation of dissolved argon in water from some confined wells in Nagoya and Matsumoto.

METHODS

Principle of the present method.—Even if a maximum of gas content appears in water, we cannot always tell the year of its initial permeation. If more than one year has elapsed since the water soaked into the ground, we cannot decide whether a maximum of dissolved gases means the preceding winter. The method must therefore be applied in a field where the source of ground water is well known and where the direction of water movement is easily estimated. Further development of Oana's method was tried by the following two ways, which were then compared: (1) The test wells chosen were situated along the direction of ground water flow, and the amount of dissolved gas was measured in each well every month; the effective velocity of ground water was estimated from the lapse of time for attainment of maximum dissolved-gas content. (2) The amount of dissolved gases was measured in many wells at about the same time, and isopleths were drawn. From the locations of maximum and minimum values of dissolved gases the effective velocity of the ground water movement was estimated.

Sampling and experimental methods.—Water samples were taken from artesian wells by inserting the tip of a siphon about two meters below the casing head in order to avoid contact with air. Dissolved gases are driven out of the water sample by means of Winkler's carbon dioxide method as modified by Sugawara (1939). The total volume of dissolved gases minus carbon dioxide is measured manometrically. Oxygen is determined next by difference after absorption by an alkaline pyrogallol solution. The remaining gases are determined mass-spectrometrically.

Description of the field.—The foregoing methods were applied to the field around the town of Takada, in the prefecture of Gifu. In this region the Makita River runs into an alluvial plain from a mountainous hinterland composed of Permo-Carboniferous rocks (fig. 1). Except during the rainy season, the river ceases to flow on the surface at or below its point of entrance onto the plain. Water that disappears from the river bed is supposed to become confined water beneath the alluvial plain. This ground water should flow southeastward in the direction of the surface slope, for the following reasons: (1) A contour map of the water table published by Murashita and others (1954) shows that the water table dips to the southeast. (2) The dip of the aquifer and the surface inclination of the plain accord with each other (figs. 1 and 2). (3) The

character of the ground water changes in that direction; that is, its content of sodium, potassium, total cations and bicarbonate increases in that direction, while calcium and magnesium decrease.[1]

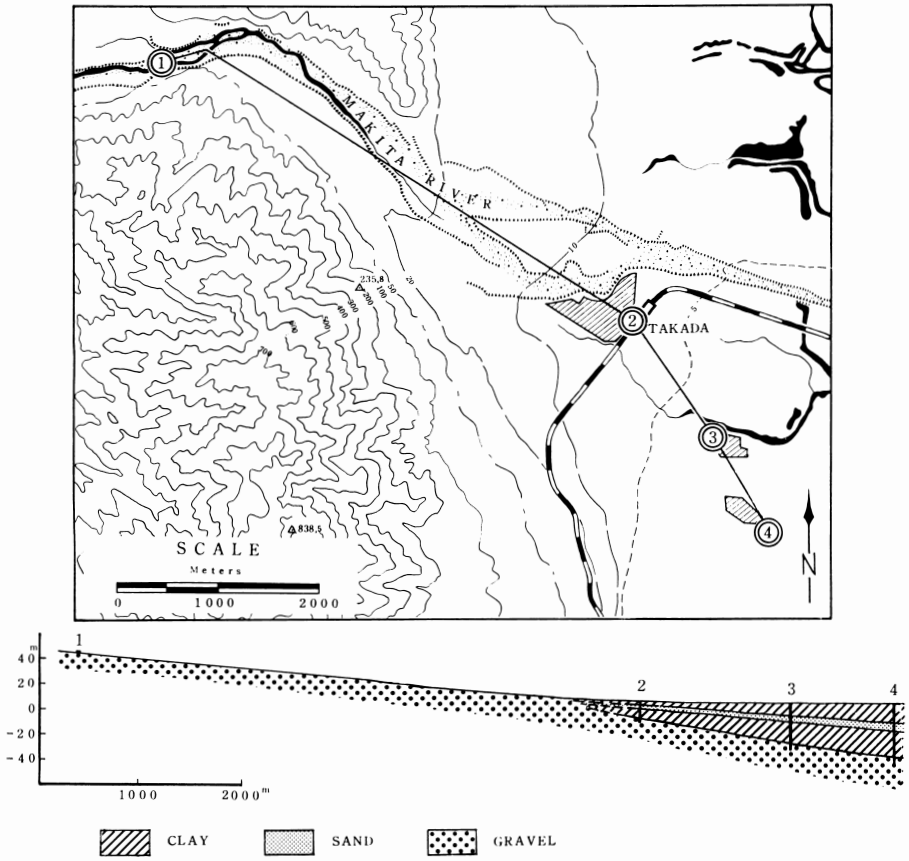

Fig. 2. (Above) topographic map showing locations of samples for successive measurement; (below) geologic section showing well depth.

RESULTS

Successive measurement of dissolved gases.—The mass-spectrometric determination shows that the content of dissolved methane is very low in this field; its maximum value is only 0.05 ml/L. No higher hydrocarbons were detected. Therefore the dissolved gases, after oxygen is subtracted, consist of nitrogen and argon. The amount of dissolved nitrogen may change due to denitrification of nitrogen-containing compounds and to the fixation of nitrogen. In this area, however, where the production of methane is very weak, we can expect no appreciable change of dissolved nitrogen. Nitrogen and argon can therefore be used as tracers.

[1] This may be due in part to base exchange. However, the increase of sodium and potassium exceeds the equivalent amount expected after base exchange. The excess may be derived from specific dissolution of sediment.

Three test wells were chosen; they are located along the supposed direction of flow and belong to the same aquifer (fig. 2). Nitrogen and argon were determined in each well water once a month during the period between February 1955 and March 1956.

TABLE 1

Effective velocity by successive measurement

Station*	Distance in meters	Time Interval in months	Effective Velocity in meters/day
1–2	5000	2	84
2–3	1500	5	10
3–4	1100	10	3.6

* Station 1, Makita River; station 2, test well 1; station 3, test well 2; station 4, test well 3.

Figure 3 shows that test well 1 (station 2) has a maximum value in April and a minimum in October; test well 2 (station 3) has a maximum in September; test well 3 (station 4) has a maximum in July and a minimum in

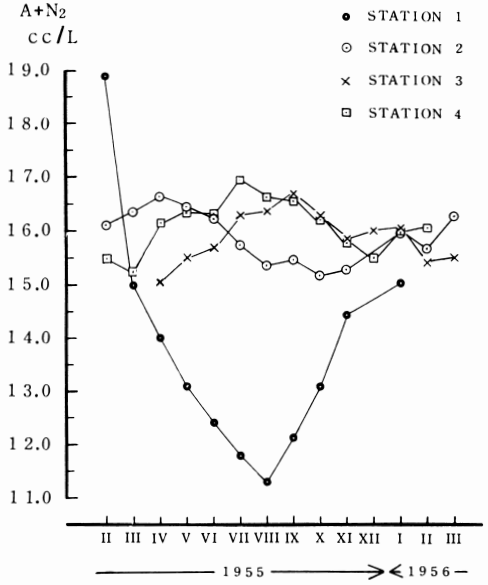

Fig. 3. Successive variation of dissolved nitrogen and argon in river water (station 1) and test well water.

December. Also shown in this figure (station 1) is the variation of nitrogen and argon in river water at the spot where Makita River water disappears from the bed. The maximum is in January when the water temperature is 4.7°C and the minimum in August when the water temperature is 25°C. From

the time-displacement of the maximum value of dissolved nitrogen and argon between one station and the rest, the velocity of ground water flow is calculated. It takes two months for ground water to reach test well 1 after sinking underground; five months to move from test well 1 to test well 2; ten months from test well 2 to test well 3. The effective velocities are calculated from these time intervals and the distances between the stations as shown in table 1.

Simultaneous measurement of dissolved argon.—On the basis of the principle mentioned above, 24 wells were selected in this field, and dissolved argon was measured during a short period between May 28 and June 12, 1958. The result is shown in table 2. Argon is perfectly inert, so we can trace its behavior without any interference from chemical reactions. Oana (1957) determined the content of dissolved argon in water which is in gas exchange equilibrium with air under 1 atmosphere pressure. His results suggest that the temperature of water at the time when it soaked into the ground may be cal-

TABLE 2

Dissolved argon content and estimated "original" temperature of water by simultaneous measurement

Station number	Dissolved argon content ml/L	"Original" temperature of water** °C
1	0.38	9
2	0.42	5
3	0.32	17
4*	0.34	14
5	0.34	14
6	0.37	10
7	0.36	11
8	0.33	15
9	0.28	23
10	0.35	13
11	0.30	17
12	0.26	27
13	0.42	5
14	0.35	13
15	0.41	7
16	0.33	15
17	0.36	11
18	0.28	22
19	0.46	2
20	0.37	10
21	0.43	4
22	0.47	0
23	0.34	14
24	0.31	17

* Station 4 is test well 1 in table 1.

** Temperature of water on entry underground is calculated from Oana's measurements (1957) of solubility.

culated from the argon content observed. Temperatures calculated in this way are shown in table 2.

The contour lines (isopleths) in figure 4 show the distribution of the temperature values so calculated. Figure 5 shows the relationship between the "original" water temperature and ground water movement along section A-B. The distance interval from one minimum temperature to the next minimum in this curve corresponds to a time period of one year. The effective velocity of ground water between the test wells used for the successive measurement is recalculated on the basis of the simultaneous measurements, and the results are given in table 3.

TABLE 3

Effective velocity by simultaneous measurement

Station*	Distance in meters	Time Interval in months	Effective Velocity in meters/day
2–3	1500	6	8.4
3–4	1100	7	5.8

* Stations have the same number as in table 1.

TABLE 4

Converted velocity (by Darcy's formula*) for a one percent hydraulic gradient

Station†	Hydraulic Gradient** (percent)	Converted Velocity (meters/day) Successive Measurement	Simultaneous Measurement
2–3	0.2	51	42
3–4	0.1	36	58

* Darcy's formula is $V = k \cdot h/l$, where V is effective velocity of ground water, h/l is hydraulic gradient, and k is constant.

** Value published by Murashita and others (1954).

† Stations have the same number as in tables 1 and 3.

DISCUSSION AND CONCLUSIONS

It may not be fair to use Darcy's law to compare the present result with data published by other investigators, because the test aquifer contains very coarse gravels (1 cm to 50 cm in diameter) with small amounts of pebbles and sand, whereas Darcy's law is usually applicable to fine-grained sand beds. However, if we assume that Darcy's law can be applied to such an aquifer, and use the hydraulic gradient published by Murashita and others (1954), the present result can be converted into the velocity for a one percent hydraulic gradient (table 4). Tolman (1937, p. 219) published the value of 33 meters per day as the average velocity in coarse gravel for one percent hydraulic gradient. Usually the average velocity is a little lower than the effective velocity. Therefore, the effective velocities observed (36 to 58 meters per day) seem to be reasonable.

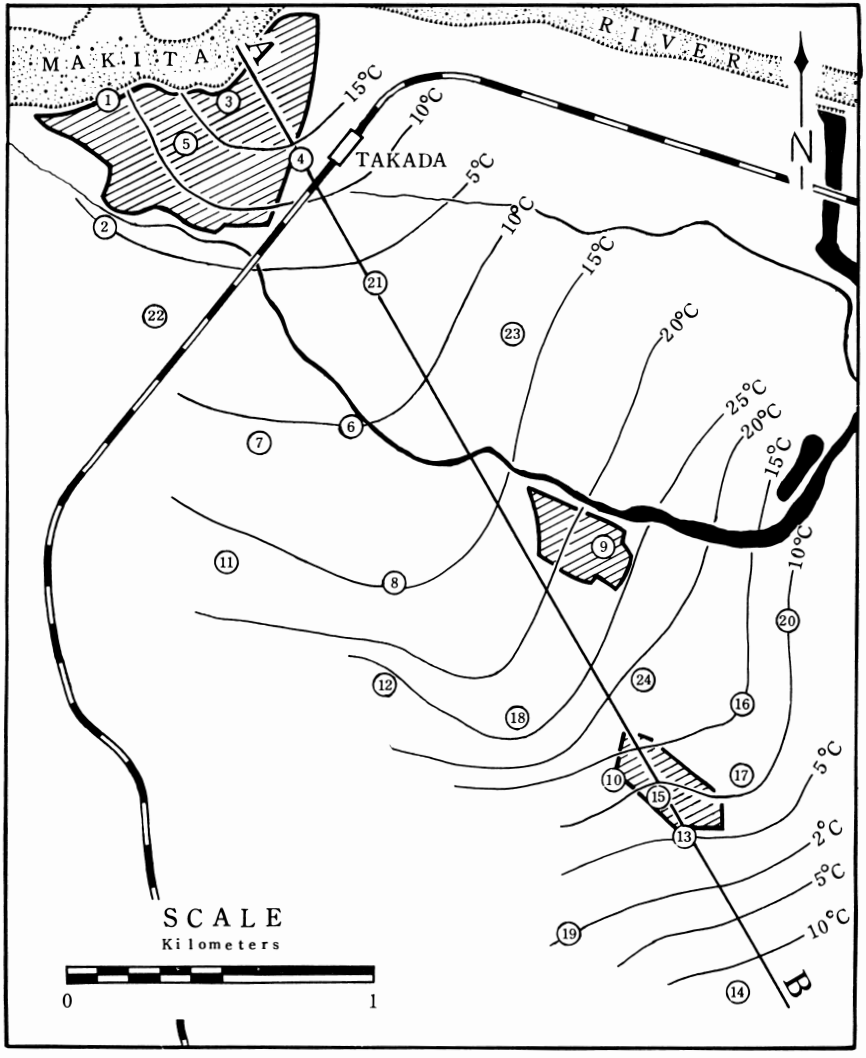

Fig. 4. Contour lines of "original" temperature of ground water; circled numbers are numbers of stations in table 2.

The results from the two methods of observation, successive and simultaneous, are self-consistent, indicating that the methods are reliable.

In table 1, the velocity from station 1 (river) to station 2 (test well 1) is very large. This large value is mainly caused by inexactness in estimating the distance between stations: (1) Water taken at station 1 is surface water, and uncertainty is inevitable about the starting point of seepage; that is, river water is always observed at station 1, even in the dry season, and it disappears from the river bed just beyond this station, but in the rainy season it

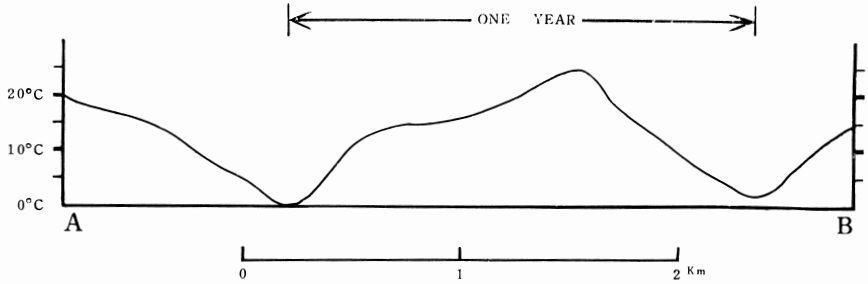

Fig. 5. Variation of "original" temperature in section A-B in figure 4 (ordinate: temperature of water on entry underground).

flows farther. (2) The clay bed known at station 2 does not extend as far upstream as station 1 (fig. 2). Therefore, ground water in this area is believed not to be confined.

The fact that the measured velocities decrease downstream may be due to the decrease of hydraulic gradient and/or to the increased thickness of the aquifer.

Some practical remarks on the method are the following: (1) The amount of dissolved nitrogen can vary for biochemical reasons in a field where ammonium or nitrate ions are found in appreciable quantities. Thus nitrogen would not be appropriate as a tracer in such a field. (2) Successive measurement is favorable in a field where suitable wells are rare, but cannot be applied if it takes more than one year for water to move from one test well to another. Simultaneous measurement has the advantage that the velocity can be determined in a short period of time, but it cannot be applied to a field having only a few wells. In any case, it is necessary to select test wells that belong to the same aquifer. (3) The application of this method is restricted to fields where water is supplied from a limited source and the direction of ground water current is known. In the case where several water masses contribute to the aquifer at different points, it will be difficult to use this method. On the other hand, if the contaminating water mass is relatively small, simultaneous measurement may detect it, for such a contamination should be indicated by distortion of the contour lines of dissolved argon. (4) From a geochemical point of view, it would be interesting to compare this method with the natural-tritium method, because both are suitable for ground water moving through large areas with seepage times measured in years.

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