J. FAC. SCI., SHINSHU UNIVERSITY Vol. 18, No. 1, 1983

On the recovery process of the groundwater depression cone in a high permeable aquifer

By HISAO KUMAI

Department of Geology, Faculty of Science,
Shinshu University
(Received 9th Dec., 1982)

Abstract

The shape and recovery process of the groundwater depression cone in a high permeable aquifer which has a steep inclination water table, are different from those in a gentle area. As an example, the author investigated the characteristics and movement of the influence circle caused by the yield of a very large quantity of groundwater due to digging for building construction. In the case of an inclined groundwater table as in a fan, the influence circle caused by the yield of groundwater by a well is in general deformed and elongated in the downstream direction. As a result of the present study, it can be said that the same pattern occurs in conjunction with the yield of a very large quantity of groundwater such as by digging for construction, althogh there are some differences in relation to the nature of the aquifer condition and recharge mechanisms.

Moreover, after decrease or stop of the groundwater yield from the digging site, the influence circle did not disappear soon, but remained for several days more after the stop of the yield. The groundwater table recovered from upstream as if a flood wave and the center of the influence circle moved downstreem at almost the same rate as the natural velocity of the groundwater flow in the area.

1. Introduction

In a homogeneous unconfined aquifer with an almost horizontal groundwater table, the three dimensional form of the depression cone caused by the yield from a well is that of a symmetrical cone. However, in the case of an inclined groundwater table, the cone of depression is deformed by the groundwater flow, and the influence circle is elongated in the downstream direction[1]. Such a case was observed at the time of digging for preparation of the foundations for construction of building in the southern suburbs of Matsumoto City. It was found that the cone of depression shrank away and center of the cone moved downstream after stopping of the yield.

From September 1976 to March 1977, digging for the building of the Minami-matsumoto branch office of Nippon Telegraph and Telephone Public Corporation was carried out with a large quantity of groundwater discharge. The scope of the digging cavity was about 1,200m^2 in area and the maximum depth was 7.60m (average depth 4.2m).

As a result of this yield, the groundwater table of the wells around the digging site was drawn on by interference. Before the digging, Nippon Telegraph and Telephone Public Corporation performed a geohydrological survey with pumping tests to obtain data for forecasting the draw down of the groundwater table around the site, and established 21 observation wells for monitoring around the site. In this paper, those records are used to make a geohydrological analysis of the phenomenon as mentioned above.

2. Geomorphology and geology

The investigated area in this paper comprises Takamiya and its environs, in

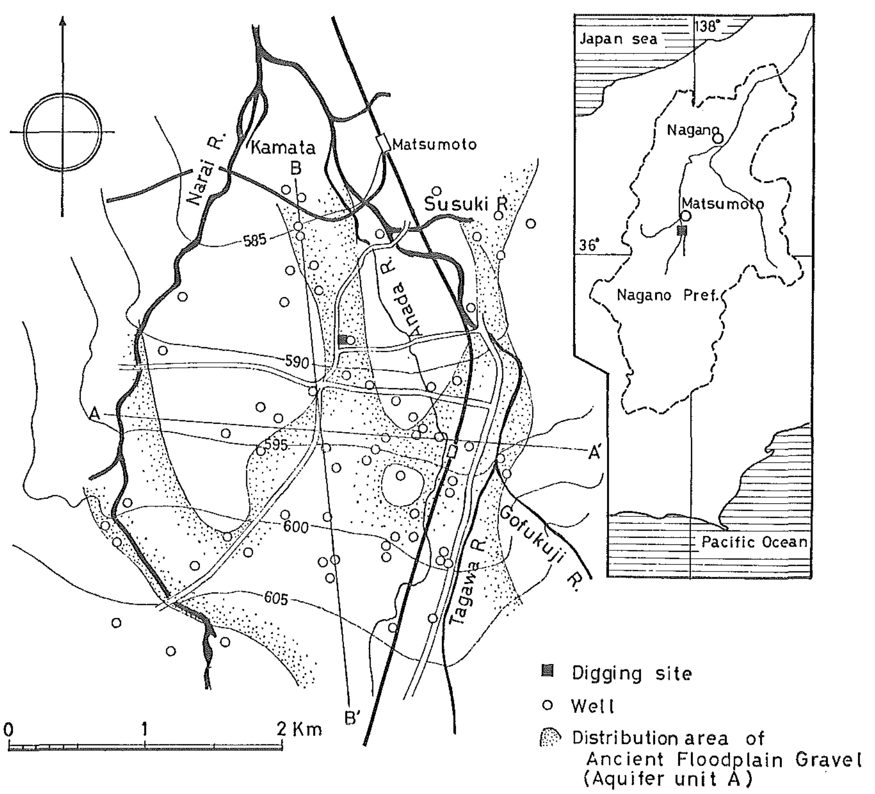


Fig. 1 Map of the invstigated area. The contours show the ground surface altitude

the southern part of Matsumoto City. This area is situated in the southeastern part of Matsumoto Basin, where part of the Alluvial plain enclosed by the Narai River and Tagawa River, both of which are branches of the Sai River, is situated. The ground surface in this area is inclined generally towards the north at an angle of about 1/125, with an altitude of around 600m (Fig. 1.).

Lowest Terraces* of uppermost pleistocene are distributed at the surface about 4 km southwards from this area. They are present subsurface in the area, which is situated on the edge of the Narai River Fan, and in the boundary region between the paddy fields (northern) and farms (southern). The area adjoins the Azusa River Fan to the west, and the Susuki Riuer Fan and Gofukuji River Fan to the east. Many springs are therefore situated in the area which is rich in groundwater resources.

The amount of spouting water from the springs increases annually in March and April, and decreases after September. Some of the springs stop in winter. In this area, the ground surface is so flat that there are no outcrops of strata, and the stratigraphy cannot therefore be observed directly. Nevertheless, the overall geology can be inferred from the many columnar sections of wells which have been drilled in the area.

A record exists of 150m of all core boring drilled at Yoshikawa Primary School about 1km south from the southern edge of this area[2)]. Using the record of this boring which contains analytical data on heavy minerals, pollen and diatoms, and also referring to the stratigraphy around the Matsumoto Basin, as studied by the Matsumoto Basin Collaborative Research Group[3)], the geological units in the cores are tentatively correlated as described below in ascending order.

A. Nashinoki Gravel Formation (140～150m^{+}).

This formation is composed of loamy clay or a fine sandy matrix with weathered gravels termed "Kusare reki".

B. Nakayama Peat Formation** (68～140m).

This formation is composed of gravels with a clayey matrix and is intercalated in part with a few peaty silt beds. Based on heavy mineral analysis of the loam beds intercalated in this formation, it is correlated with the Osakada Loam Formation. Pollen analysis of the formation has yielded a few pollen fossils such as Cyperaceae, *Cirsium*, *Chenopodium*, and Graminae. The results of diatom analysis were negative. It is inferred therefore that this formation was accumulated very rapidly.

---

* These Terraces are capped by the uppermost part of the Hata Loam which is overlain by Alluvial Gravel near Matsumoto Airport at Imai, Matsumoto City.

** At the type locality, this formation is composed of peat beds, so accounting for the proposed name. However, at other localities it does not always present a peaty facies.

C. Hata Gravel Formation and Moriguchi Gravel Formation (about 50*～68m).

This formation is composed of gravels with a tuffaceous matrix. It is intercalated at 60.67～61m below the surface by a "White Tuff" which is one of the key beds of the Hata Loam Formation[4].

D. Alluvium (0～about 50m*).

This formation is composed of well sorted gravels and alternations of fine gravel and sand.

On this basis, the stratigraphy of the area as summarized in Fig. 2 in the form of geological profiles, is correlated as follows. The gravel bed and gravel with clay bed which lie just below the surface are correlated with the Alluvium, and in particular the former corresponds to the Ancient Floodplain Gravel. The sand and gravel beds which lie at 50～60m below the surface are correlated with the lower part of the Alluvium, the Moriguchi Gravel Formation and Hata Gravel Formation. The still underlying beds are correlated with the Nakayama peat Formation.

3. Condition of aquifers

The groundwater table in this area is shallow and is almost parallel to the

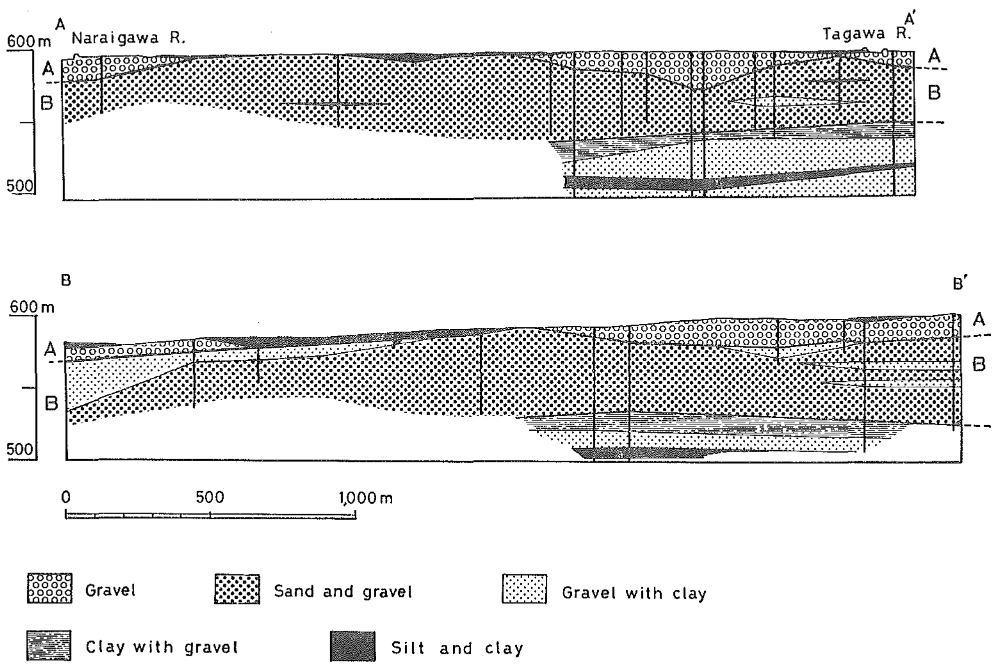


Fig. 2 Geological profiles (cf. Fig. 1.)

* The stratigraphy of the core above −50m is not complete since this section was cut by the percussion drilling method.

ground surface. Virtually all of the groundwater in the area is unconfined within the Pleistocene deposits and Alluvium described above. The most useful and rich aquifer is within the Ancient Floodplain Gravel, which is here denoted as aquifer unit A. All the aquifers within the Pleistocene deposits and the remainder of the Alluvium are referred to as aquifer unit B.

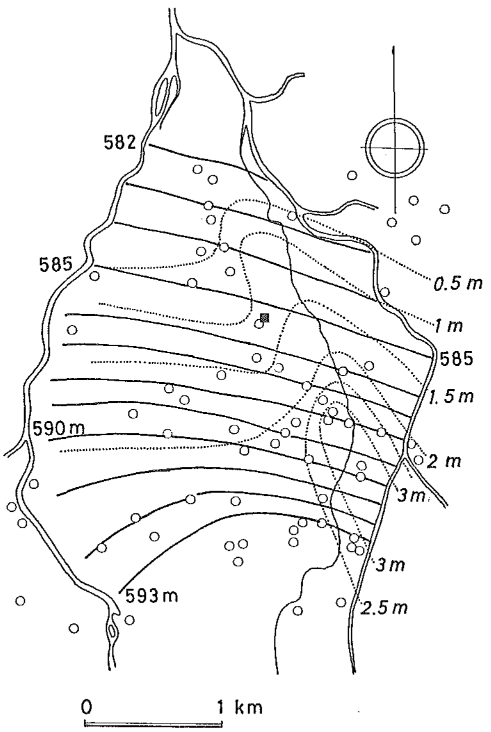


Fig. 3 Distribution of specific capacity in m^2/day.

The distribution of the Ancient Floodplain Gravel is shown in Fig. 1. This formation occurs widely in the upstream part of the area, but then becomes narrow in the central part of the area. The digging site was situated just on a channel in this gravel formation with a width of about 300m.

The features described above suggest that the groundwater flow is restricted by the difference in permeability between the aquifer units A and B, and spouts out as springs. In fact, many springs present in the area do spout out all by the above mechanism. In this connection, the distribution of the specific capacity in the area reveals the same characteristics. As is readily seen from Fig. 3, the digging site was situated in an excellent aquifer whose specific capacity is well over 2,000m^3/m/day, and is in the center of the groundwater stream from Gofukuji to Kamata. A large quantity of yield at the digging site could thus be expected to exert a strong effect on aquifers in the downstream area.

Pumping tests* were carried out twice at this site prior to digging. The results in both tests as calculated by Theis' method, were as follows.

Coefficient of transmissibility T: 0.190m^2/sec

Coefficient of permeability K: 0.019m/sec

Coefficient of storage S: 0.155 (non-dimensional)

* The pumping test were carried under the following conditions.
Pumping well diameter 0.5m; depth 11m; steel pipe with screen.
Observation holes diameter 0.05m; depth 10.5m; 12 holes of vinyl-chloridation pipe were set in a direction towards east Chloridation and north from the pumping well.

The results of other pumping tests performed at places in the same area prior to the above tests are listed in Table 1.

Table. 1. Coefficients of aquifers around the digging site

Loc.	Aquifer	T(m²/sec)	K(m/sec)	S
Idegawa–Takamiya Junction	Aquifer unit A	0.183	3.03×10^{-2}	0.0429
Igawa–jo	Aquifer unit B	0.213	4.73×10^{-3}	—
Ryojima	Aquifer unit B	0.158	3.37×10^{-3}	0.0248

As a consequence of pumping at the test well, the ground–water table at each observation hole was found to be little affected at the beginning. Expansion of the influence circle around the pumping well was not really very rapid. For example, after 5 hours of pumping, one hole which was 31m distant from the pumping one in the downstream direction showed effects of draw down, whereas another hole at a distance of 41m revealed no effect at all on the groundwater table.

On the basis of the above results, the velocity of expansion of the influence circle in the downstream direction was estimated to be between 6.2m/hr and 8.3 m/hr. The velocity of expansion in the cross direction, i. e. in the E–W direction of the stream, was faster than that along the flow line, since the influence was already apparent at an observtion hole 63m distant from the pumping well at 5 hours after pumping started.

4. Effects of digging for building construction accompanied by groundwater yield

The foundation digging for the construction operation began in September 1976 into aquifer unit A as mentioned above. During the digging until its completion on March 20, 1977, there was a continued yield of groundwater with a maximum of 0.87m³/sec (February 15). In order to estimate the influence of the yield of groundwater at the digging site, 21 wells were newly selected for observation of the groundwater table.

The influence circle was widespread and the water table in the observed wells showed draw down or even dried up. The data for the volume of groundwater yield until the end of construction were as follows.

Feb. 25	0.7m³/sec
Mar. 1	0.55
5	0.40
10	0.33
15	0.27
20	end of pump up

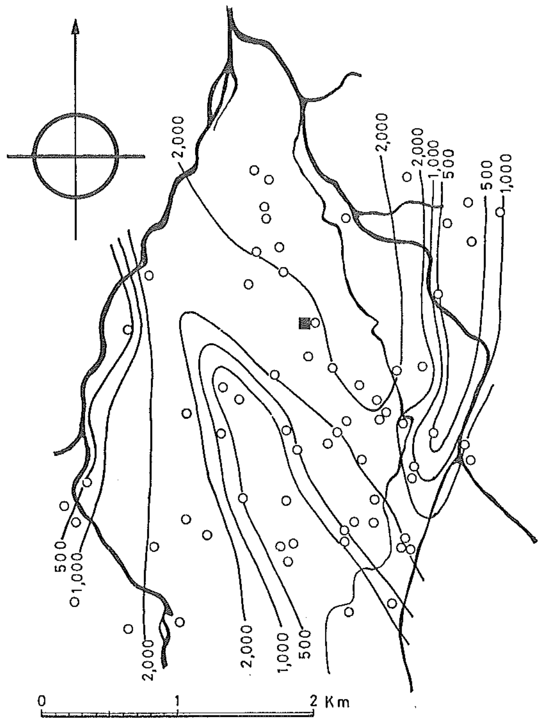


Fig. 4 Distribution of the groundwater table high as altitude before construction (May 12, 1976), and the groundwater table rise from May 1 to May 12.

After stopping of the pump, the water table in each observation well rapidly recoverd. Until that time, the influence circle had been widespread. Movements of the groundwater table were traced day by day (Fig. 4). On March 3 and March 9, pumping up was still continuing, but decrease in the groundwater yield had already started at that time. On March 3, the total volume of groundater flow passing through the cross section parallel to the equipotential line near the digging site (A–A′) was calculated by Darcy's law as follows.

A. Groundwater flow (Q_f) in aquifer unit A

$$Q_f = A_f K_f I \qquad (1)$$

A_f: Area in profile section, 12,000m^2

K_f: Coefficient of permeability, 0.019m/sec

I: Gradient of groundwater table, 1/125

$$Q_f = 1.82\text{m}^3/\text{sec}$$

B. Groundwater flow (Q_a) in aquifer unit B

$$Q_a = A_a K_a I \tag{2}$$

A_a: 113, 000m²

K_a: 3. 37×10⁻³m/sec

$$Q_a = 3.05\text{m}^3/\text{sec}$$

C. Total volume (Q_t)

$$Q_t = Q_f + Q_a = 4.87\text{m}^3/\text{sec} \tag{3}$$

Based on this calculation, it can be said that the yield from the digging site represented about 14~5% of the total flow in this area.

The extension of the influence circle can be calculated by Smreker's method[1] as follows. First, the diameter of the influence circle parallel with the equipotential line is calculated from the equilibrium formula since it has no relationship with flow.

$$\log r_e = \log r + \frac{2\pi T s}{2.3Q} \tag{4}$$

r: Distance from digging site

s: Draw down of r-point

r_e: Diameter of influence circle

Q: Yield

The draw down of observation well No. 4 (about 300m westwards from the digging site) was about 2m on March 3.

$$\log r_e = \log 300 + \frac{2\times 3.14\times 0.19\times 2}{2.3\times 0.5} \tag{5}$$

$$r_e = 36,000\text{m}$$

The results of the calculation indicate an extremely wide influence caused by digging. However, the edges of the influence circle are cut by the Tagawa River and Narai River, since both are recharge rivers.

The culmination point, p_0 (Kulmination Punkte), of Smreker[1] was estimated as follows.

$$r_t = \frac{Q}{2\pi f H C} \tag{6}$$

r_t: Distance from digging site to p_0

f: Effective porosity

H: Thickness of aquifer

C: Groundwater velocity

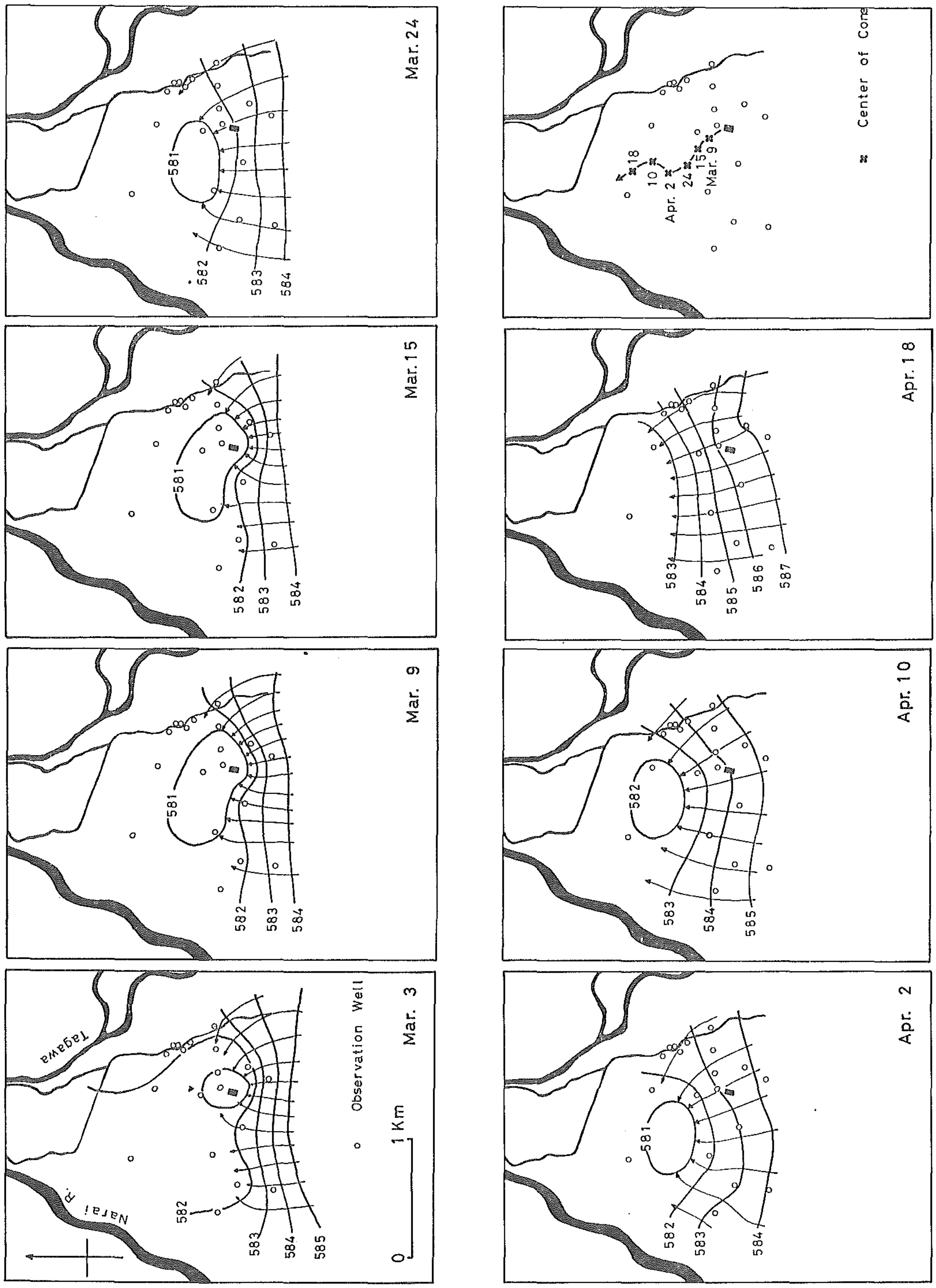


Fig. 5 Recovery process of the depression cone. The digging site is shown by the black square, the culmination point as a black triangle, and the contours indicate the groundwater table high as altitude.

In this expression, f can be replaced by the coefficient of storage (S) and $H\,C$ can be transformed $T\ I$, where T is the coefficient of transmissibility and I is the gradient of the groundwater table.

Equation (6) thus becomes

$$r_t = \frac{Q}{2\pi STI} \tag{7}$$

On March 3, the relevant data were

Q: 0.5m³/sec

S: 0.155

T: 0.19m²/sec

I: 1/125

Therefore,

$$r_t = \frac{0.5\times 125}{2\times 3.14\times 0.155\times 0.19} \tag{8}$$

$$= 337.9\text{m}$$

The point p_0 is shown in Fig. 5. as a black triangle.

The width of the yield limit (Entnahmebreit)[1] (L) can be calculated as follows.

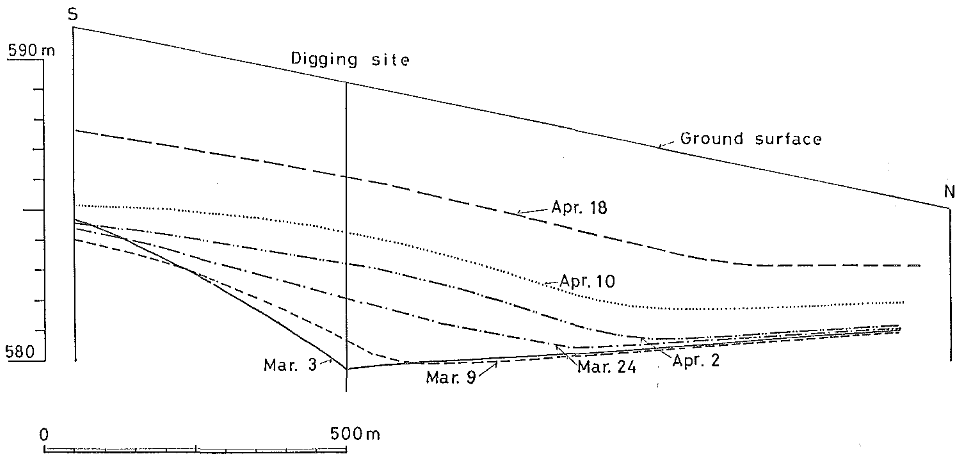
$$L = 2\pi r_t$$

$$= 2,122\text{m}$$

This figure means that flow lins in a range of about 1km on either side of the digging site should theoretically be concentrated towards the digging site. In reality, the flow lines were seen to be concentrated on the digging site as indicated in Fig. 5, in accordance with calculation.

5. Recovery proccess of the depression cone

Flownets before and after stopping of the yield in this area based on the water level of the observation wells, are illustrated serially in Fig. 5. A clear cone of depresion remained until April 10, and the center of the cone moved downstream with lapse of time. The recovery process in profile section parallel to the groundwater flow lines is shown in Fig. 6. The groundwater depression cone appeared to move downstream with shrinking, while the groundwater table recovered rapidly from upstream. This phenomenon was promoted by the wide influence circle diameter of the crossed flow line. The recharge distance from the side was so great and the gradient of the groundwater table was so gentle that the velocity of recharga from the side was less than that from upstream. The velocity of the movement of the center was about 17 m/day (Fig. 7).



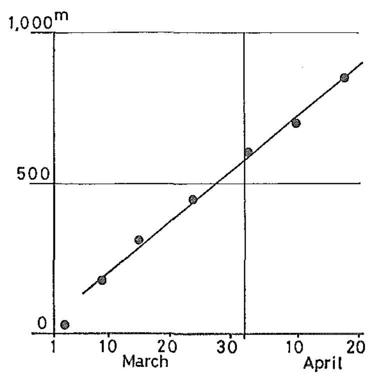


Fig. 6 Recovery process of the groundwater table in profile section as represented by the crossed contour lines of for the groundwater table high.

Fig. 7 Moving velocity of the center of the influence circle.

The rate of water table recovery was about 1 m/8 days, which was about the same as the value of the natural recovery rate of the groundwater table in this area at the same season, of about 1m/10 days. The observed recovery may thus have been due mostly to natural recover. In addition, the natural velocity of the groundwater flow in this area may be expressed as follows.

$$v = KI \tag{10}$$

I is almost identical to the gradient of the surface. and K is the coefficient of permeability of aquifer unit A (0.019 m/sec). Therefore, v is about 13 m/day.

On rising of the groundwater table, there are two modes of recharge. One is lateral recharge of water passing through within the main aquifer, and the other is vertical recharge such as by the leakage of rain. In the present case, the main route of recharge must have been the lateral one, since the total precipitation in this period was about 190.5mm (Fig. 8). If it is assumed that all of the precipitation leaked into the aquifer, the total rising of the groundwater table would be about

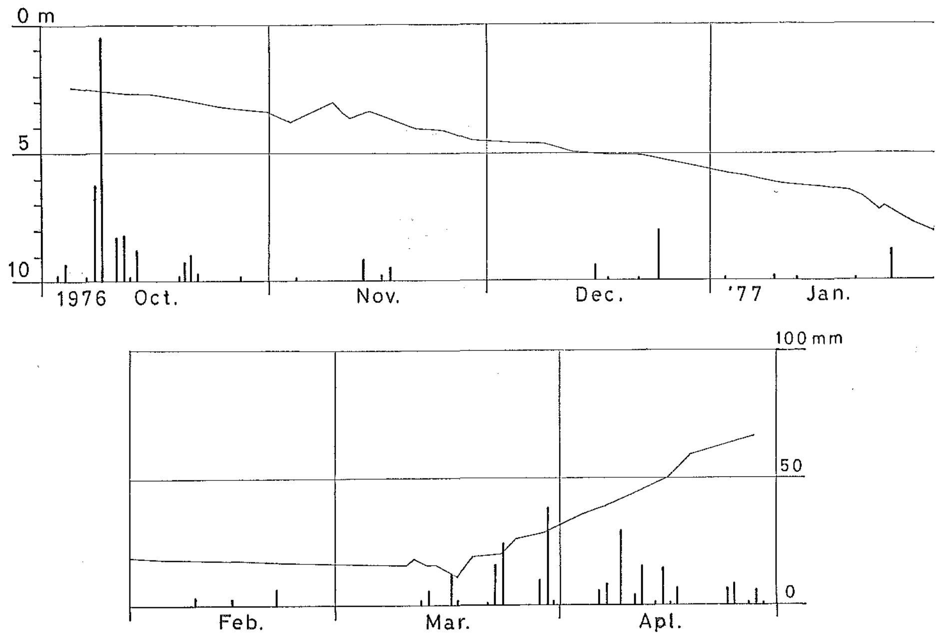


Fig. 8 Groundwater table fluctuation at the digging site. The bar graph shows the precipitation at Matsumoto.

1.229m, which is only about 35% of the total amount of rise. Also, after May 24, it happened as rising all round. The precipitation may have acted to lift up the water table as a whole, and not to cause the disappearence of depression cone by itself see Fig. 5 (may. 24～Apr. 10) and Fig. 6.

On the basis of the above results, the groundwater table recovery process in a high permeable aquifer which has a steep inclination water table is considered to be as follows. The influence circle expands downstream and the cross direction to the flow line shrinks by lateral recharge. At that time, the main recharge originated from upstream. Therefore, the depression cone appears to move downstream with the same velocity as the natural groundwater flow after decrease of the yield.

6. Acknowledgements

The author wishes thank the staff of the Shinetsu Telecomunications Bureau, Nippon Telegraph and Telephone Public Corporation for their supply of data. He is also grateful to prof. the late Yasuma Gohara, Dept. of Geology, Shinshu Univ., for his helpful suggestions during the course of this work and to Dr. Makoto Kato, Dept. of Geology and Mineralogy, Hokkaido Univ., for critically reading the manuscript.

Thanks are also due to Miss Yukiko Otomo, Mr. Kenji Tobita, the late Yasutaka Tsuzuki, Mr. Takafumi Nakata, Mr. Yuichi Nakashima and Mr. Hiroyuki Yamamoto, Miss Kazuko Koura, staff of the Dept. of Geology, Shinshu Univ., for their kind cooperation in the preparation of flownet maps and data compilation.

References

1) Sakai, Gunjiro (1965) : *Geohydrology*. Asakura-shoten, 418.

2) Planning Department, Kanto Regional offices of the Ministry of Agriculture Forestry and Fishery (1979) : The report of the investigation for groundwater preservation and recharge on Southern Part of Matsumoto Basin, 40.

3) Matsumoto Basin Collaborative Research Group (1977) : The Quaternary geology of the Matsumoto Basin, Central Japan, The Memoirs of the Geological Society of Japan, No. 14, 93–102.

4) Matsumoto Basin Collaborative Research Group (1972) : The outline of the Quaternry geology of the Matsumoto Basin, The Memoirs of the Geological Society of Japan, No. 7, 297–304.