EXPERIMENTS FOR DETERMINING THE VARIATIONS OF GROUNDWATER FLOW VELOCITY WITH DEPTH

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As regards groundwater flow velocity and the quantity thereof, basically different opinions have been voiced by individual researchers. These disagreements have their motives, because the determination of groundwater flow quantity is one of the most difficult tasks in geohydrological research. Direct measuring methods to determine groundwater flow velocity and quantity are unknown as yet. Therefore, based on different computation methods, efforts are made to draw conclusions concerning groundwater flow velocity and quantity, some features being determined by measurements, others by values estimated.

When determining groundwater flow extending over a larger area it is generally the groundwater gradient only, which can be established with satisfactory accuracy. Determination of the seepage coefficient, however, involves a great number of uncertainties. Relying upon Darcy's law, from groundwater gradient and from the permeability coefficient seepage velocity, then — applying free pore volume — the actual velocity can be computed. Yet, two further difficulties are to be faced. The first is caused, whether the way of continuous flow is ensured with regard to soil stratification when extending over larger areas, *i. e.* what obstacles and head losses are indicated by stratigraphic variations, the second question to be answered is, whether the gradient of groundwater table observed on larger areas is in accordance everywhere with flow velocity and quantity.

As can be seen, right at the beginning many uncertainties appear. Even if these features may be determined with sufficient accuracy, it is but flow velocity on whose value reliable data can be obtained. In order to compute seepage flow quantity the *flow cross-sections* should be known as well. Based on considerations it is very likely that in plainland areas, at a smaller gradient of groundwater level occurring under natural conditions, it is only the upper strip of the aquifer, which can be considered to take part in intensive water yield.

[1] Results of the experiments carried out by Research Institute for Water Resources, presented by Prof. Dr. I. Kovács

As regards fine-grained aquifers, based on theoretical considerations, it was verified by JUHÁSZ [1], that with increasing depth and water pressure flow velocity decreases considerably and even so a depth is conceivable where groundwater flow is likely to stop altogether.

As for gravel and sandy-gravel layers, the decrease in velocity has been deemed insignificant by theoretical considerations. Water household investigations as well as conclusions drawn from hydrological data have shown, that even through these gravel layers of great thickness (Little Hungarian Plain) a seepage process, whose intensity might be in accordance with groundwater gradient, cannot be assumed to exist in the entire depth.

In order to solve the technical problems of water conservancy, it is becoming increasingly necessary to determine groundwater flow quantity for larger areas and in a reliable manner. Considerable aid is offered by recent theoretical research results, these however being insufficient in themselves. Reliable data gained by applying experimental methods and direct measurements in nature are needed to settle this question.

We were led by this aim in trying to determine the velocity of groundwater flow and its variations with depth, relying on experimental measurements.

1. Selection of the experimental area

As far as soil structure is concerned, the talus of the Danube River in the Little Hungarian Plain having a sandy-gravel layer of uniform structure, of great thickness, and practically taken as almost homogeneous, has proved to be most suitable for conducting experimental measurements on groundwater flow [2].

Besides, for an experimental area properly chosen the gradient of groundwater table occurring under natural conditions was required to be relatively great in order to enable velocity measurements within a short time, even in the case of smaller observation distances. The North-Western part of the Little Plain seemed to properly meet these requirements. As stated in our previous papers, the maximum gradient in groundwater level could be observed in the region between the Danube River and Rajka where the deeper situated areas of the Little Plain are recharged by a considerable groundwater flow from the stretch between the Hainburg Mountains and the Rajka sluice, from the Danube direction.

For selecting the experimental area it was necessary also to take into account, that no disturbing circumstances were allowed to occur in the surrounding regions as to have influence upon the accuracy of tests. Disturbing factors of that kind may be *e. g.* irregular infiltration of precipitation due to topographic conditions, as well as ditches, dead branches, watercourses or ponds, respectively, wells for larger withdrawals occurring in the vicinity of the experimental area, since the groundwater regime of the surroundings may be influenced by their changes in water level.

All these aspects being taken into account, the area lying South-West of the 175 + 860 km road section of the highway between Mosonmagyaróvár and Rajka was found suitable for conducting groundwater flow experiments on (Fig. 1). In the area in question there is a sandy-gravel aquifer of great

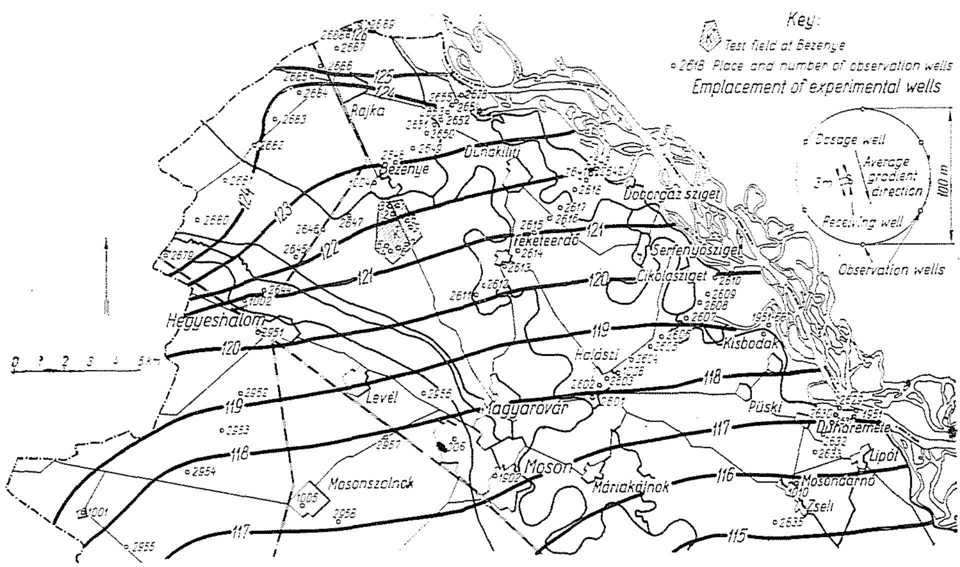

Fig. 1

thickness which can be considered as practically homogeneous overlaid by a thinner loamy-sand layer. The main direction of groundwater flow can be determined based on available observation data and the value of the groundwater gradient is fairly great here. In the immediate vicinity of this area no smaller watercourses occur and groundwater regime is affected mostly by precipitation and by a damped Danube influence.

In the experimental area preparations have been made for *accurate groundwater table observations* partly by observation wells drilled for the purpose, partly by those to be found in the surroundings. Closer delimitation of the experimental area is indicated by a circle of 100 m diameter with 6 observation wells. These are represented by the rightside sketch in Fig. 1.

2. Construction of the measuring system and decision on measurement methods

The purpose of experiments was to determine the variations of groundwater flow velocity along the vertical plane. This can be solved in the simplest way by dosing some sort of tracer into the groundwater. Out of the two vertical boreholes aligned in the direction of flow the tracer should be dosed in various depths of the upper borehole, and its appearence observed in the lower. Know-

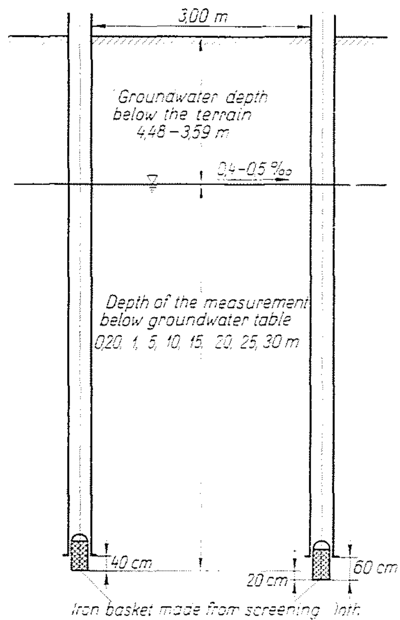

Fig. 2

ing the time elapsed from dosage until appearance and the distance between the two vertical boreholes, the average velocity of groundwater movement can be calculated $\left(v = \frac{s}{t}\right)$. Dosage of the tracer and sampling had to be carried out without disturbing the natural soil and groundwater conditions.

The first task was to determine the gradient of groundwater level and the flow direction with proper accuracy relying on repeated well observations. The average gradient direction having been determined, the locations of two wells, having a distance of 3 m from each other, had been set in the centre of the 100 m diameter circle. While gradually progressing downwards with the measurements, borings were effected at these two points without disturbing the soil layer under the chosen depth, whereas, that being over was closed up by a pipe liner. For portioning as well as receiving the tracer an iron basket enclosed in iron screening-cloth was made. At every measuring the sole of the basket got to the bottom of the boring, a 40 cm high opening was left free in the upper so-called "feed" or "dosage" well, and a 60 cm high opening in the lower observation well, while the remaining part of the upper layer was closed up by the pipe liner. Accordingly, at each depth chosen for measuring, a strip of 40—60 cm height was left free in order to enable the execution of accurate measurements as regards vertical velocity distribution. Particular attention was devoted to the requirement of the lower boring this being 10—20 cm deeper, as an eventual tracer settling was counted on. The measuring and observation devices are illustrated in Fig. 2. As for the groundwater stage daily measurements were carried out in the observation wells, and water

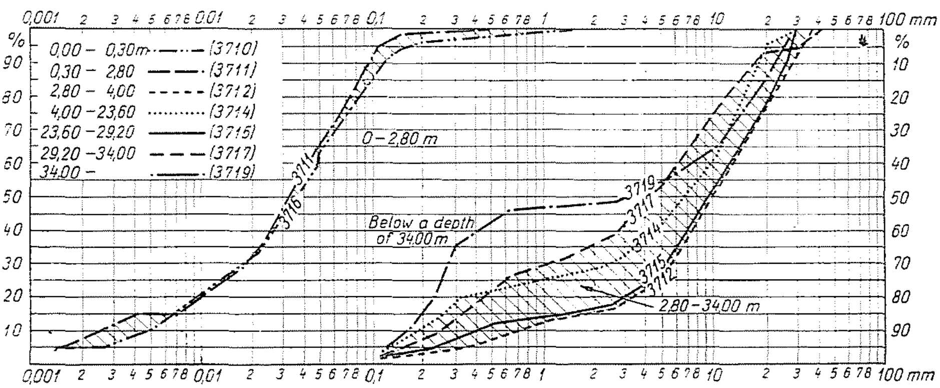

Fig. 3

samples were taken at every two hours during the tests for establishing the appearance of the tracer.

The basic principles of the experiments having been settled, the most suitable tracer and its dosage quantity had to be decided on. Under the given experimental conditions fluorescein proved at first to be the most suitable tracer. Near the groundwater surface a quantity of 15 g, at a level 1 m below groundwater table 95 g and in the following depths 500—500 g tracer was fed in. Measurements were carried out at 8 depths *i. e.* down to a depth of 0.20, 1, 5, 10, 15, 20, 25 and 30 m below groundwater level. Gradation curves of the individual soil layers are shown in Figs. 3 and 4. Control of the measurement was later performed by means of radioactive isotopes. Fluorescein dosage was so conducted as not to disturb the natural groundwater level gradient. For this reason, when measuring in the upper layer, fluorescein was dissolved in a water quantity of 5 litres, whereas for the other measurements in 10—10 litres, the concentrated solutions were placed into the basket and lowered to the bottom of the boring in thin walled bottles. The equilibrium and the water stage corresponding to natural conditions having been consolidated both in the observation wells and in the entire region, the bottles placed at the bottom of the boring were carefully broken, so as not to cause any changes either in pressure or in groundwater stage. From the point of time of breaking were the measurements begun. From then on, with the help of water samples taken every two hours, the arrival of tracer was being observed in the observation well, placed at a distance of 3 m from the dosage well.

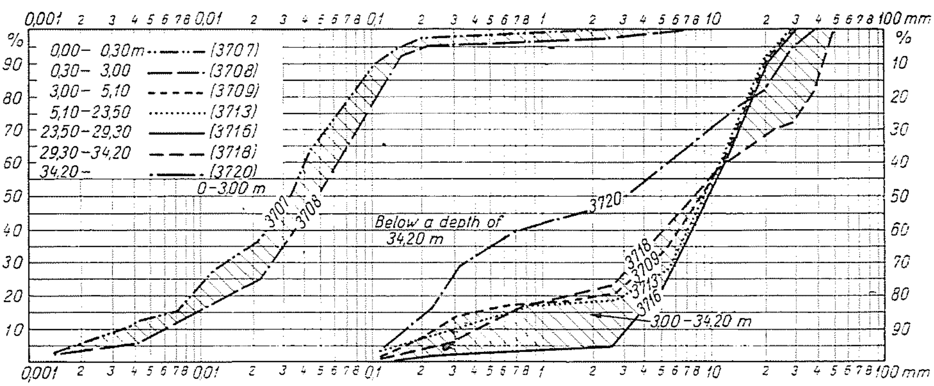

Fig. 4

3. Results of the measurement series with fluorescein

The measurements were carried out from the middle of April until the beginning of August 1959. During this period a rise in groundwater level could be experienced, while its depth below the terrain changed from 4.48 m into 3.59 m. In April and from the second half of June on until the end of the experiments the rise was relatively great, in May a moderate, whereas in the first days of June a smaller drop of groundwater level was to be observed. Also the gradient of the groundwater table has been varying during the measurements. In case of 0.4—0.5 per cent average gradient extreme values of 0.39 and 1.0 per mill were measured. The extreme values of the change in gradient were found to be —0.00695 per mill/hour decrease and +0.00286 per mill/hour increase, respectively. Both the groundwater stage and the changes in gradient as subsidiary factors had to be included when evaluating results.

Within the measuring run average flow velocities were recorded in five cases, namely at depths of 0.30, 5.40, 10.05, 15.20 and 20.40 m below groundwater level, whereas at depths of 25.25 m and 30.20 m the arrival of the tracer could not be registered in the receiving well. In these latter cases the duration of observation times took 100, respectively, 150 hours. Accordingly, the conclusion could be drawn that at these depths no significant flow exists any longer. This statement was verified by further observations as well. With the last but one measurement (25.25 m) the fluorescein contents of the water did not diminish in the feed well, even after the detailed observations were completed and a work lasting two weeks was needed to clean it out. This proved that at the above mentioned depth groundwater flow did not take place any longer, the fluorescein appeared, however, owing to the greater depression induced in the observation well. As stated, clogging did not ensue, under the

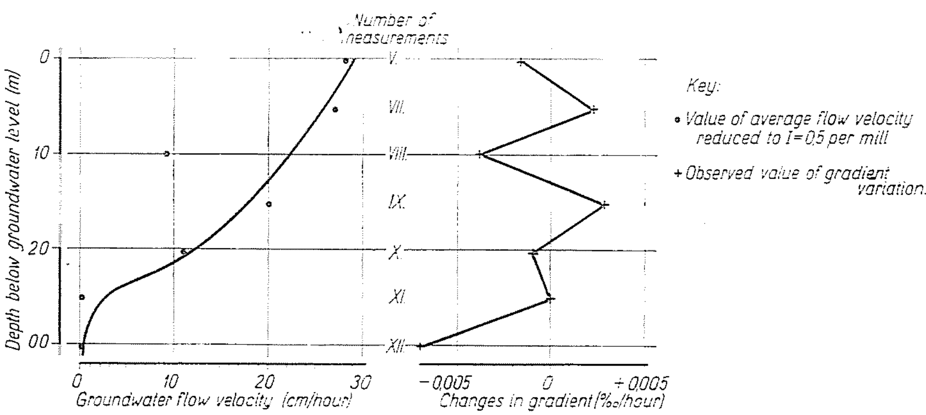

Fig. 5

influence of the great gradient groundwater flow started but seepage with a natural gradient was not experienced. As for the last measurement (30.40 m) the tracer did not appear in the observation well from the end of July until that of October, the fluorescein contents of the dosage well, nevertheless, was still significant.

As mentioned above, during the measurements also gradient changes occurred which had to be taken into consideration when evaluating the data obtained. Velocity distribution depending on depth determined by measurements and the value of gradient change are indicated in Fig. 5. The values of average flow velocity reduced to $I = 0.5$ per thousand are lying along a line of best fit, namely when having an increase in gradient a greater velocity can be observed, and conversely a decrease of the gradient results in a smaller velocity. Four measurement data are to be found close by the compensated line, whereas a considerably smaller velocity could be determined by the fifth measurement (at a depth of 20.40 m). In this latter case a significant gradient decrease was experienced, but also the soil was likely to be a little more compacted at this depth.

The maximum measured value of the average flow velocity amounted to 23.1 cm/hour (at depths of 0.30 and 5.40 m). This measured value and the general gradient being taken into account as well as assuming $n_0 = 0.20$, the seepage coefficient could be computed. Its value were found to be rather great ($>$ 1 cm/sec).

According to the results of the experimental measuring run groundwater flow velocity was found to decrease with the increase of depth, *i. e.* from the surface down to a depth of 20 m quite uniformly, below a depth of 20 m considerably, whereas below 25 m no practically perceptible groundwater flow could be detected.

4. Measurements with radioactive isotopes

During further measurements radioactive isotopes were used as tracers. Thereby, on the one hand the checking of the previous measurements was aimed at, on the other hand the possibilities of applicability of radioactive isotopes for this purpose were investigated. The measurements were carried out by making observations with radioactive isotopes at depths of 30, 20, 15, 10 and 5 m below groundwater level, the pipe liners being simultaneously withdrawn.

As isotope J^{131} was applied in the form of KJ or NaJ solution. This seemed to be suitable for this purpose, it having very small inclination to build itself into the soil and a half-period of 8 days consequently there is no danger of its contaminating the water of inhabited areas in the vicinity. J^{131} was dosed similarly to fluorescein. The ampoule containing J^{131} was opened and its contents diluted with a watery solution of about 1 litre, then inactive iodine was added, so as to eliminate the absorption of the slight active iodine by the soil. The solution was lowered the depth required in a bottle hermetically closed, then the water level having been controlled, the bottle was broken. At a depth of 30 m below groundwater level J^{131} of relatively high activity (13 mc) was dosed into the well. Based on our experiences, samples were taken from the observation well in a similar manner as with fluorescein measurements. In the beginning the activity of samples taken from the observation well was measured by a submerging GM tube *i. e.* a Radelkis-type scaler of 100 graduations. At the depth in question absolutely no activity could be revealed, not even after a month. At this latter date samples were taken at every 5 m in order to control activity in the feed well. The statement, that no sort of water movement occurs at a depth of 30 m below groundwater level could be fully substantiated. The water of the well was then still vividly green coloured from the fluorescein dosed in, two and a half month earlier and showed activity in the vicinity of the surface too. Activity in the lower water column of 20 m was found to be uniform and about three times greater than that at water surface. Within the free water column in the boring iodine diffused up to a height of 20 m, whereas in the groundwater it did not diffuse even at a distance of 3 m in the lateral direction. Based on the measurement results, the vertical diffusion velocity was found to have a value of 2.78 cm/hour (Fig. 6). That no active iodine arrives to the sampling well by any form of diffusion is also shown by the fact, that a month after feeding, when the activity of J^{131} fed in amounted to 1.07 mc, that in the dosage well was about 0.8 mc. Computations were also performed as regards the requirements for active iodine quantity, namely, as to how much active iodine was to be put into the well so as not to exceed the maximum isotope limit prescribed for

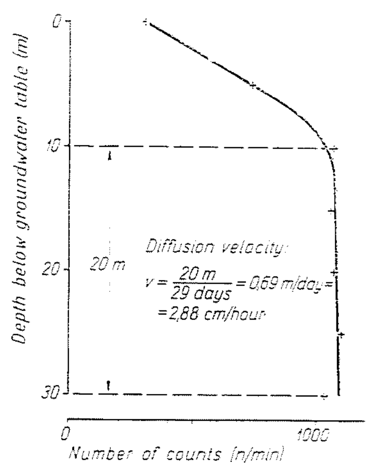

Fig. 6

the water of wells applied in the measurement area ($2. \cdot 10^{-5}$ μc/millilitre) by means of diffusion or flow, and yet to have an activity in the samples three or four times greater than background radiation. Maximum activity in the observation well at a depth of 20 m amounted to $2.8 \cdot 10^{-5}$ μc/millilitre, which nearly equals the permissible limit.

Great care was exercised also to prevent the danger of contamination when taking up the sediment on controlling the wells. For this purpose a covered canal was built, through which the sediment of very slight activity could get to a closed pit prepared beforehand and filled up after the tests. Activity of the neighbouring wells during the measurements was permanently controlled by the Institute for Public Health, pollution, however was never revealed.

Preparations for the isotope measurements were carried out in a laboratory and for field observations only active iodine in an already closed vessel was fed.

Relying on the above mentioned considerations iodine of smaller activity (4—7 mc) was dosed in course of further test stages and 1 decilitre of the water samples evaporated in each case; later the preparate was measured in a lead tower. A considerably smaller activity could be disclosed by this method than by that applied at the first measurement.

When measuring, not only counts were registered, but also the specific radioactivity of water was determined by means of relative activity measure-

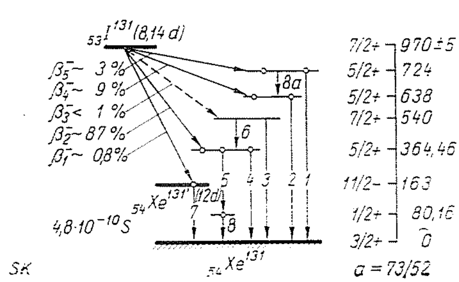

Fig. 7

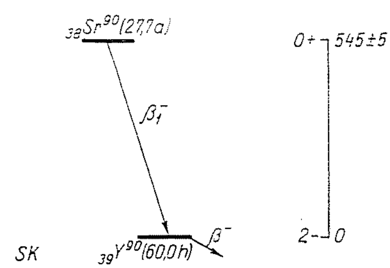

Fig. 8

ments. In order to compare, isotopes Sr^{90} having a long half-life of 27.7 years were applied as standard. Isotopes Sr^{90} can be fairly well compared with J^{131}, the energy of beta-particles flying off at decay being nearly equivalent for both (Figs. 7 and 8).

The knowledge on total activity of the active iodine in the well was constantly given, this being easily calculable on the basis of Fig. 9.

The last four measurements were carried out by simultaneously dosing also fluorescein into the well in order to compare the two kinds of measurement methods under entirely identical conditions. As regards the measurement conducted at the depth of 20 m below groundwater level (Fig. 10), a fair comparison between the two methods could be made. Almost equivalent results were obtained, yet the appearance of isotope was to be revealed with greater accuracy. At the three last measurements no results were gained *i. e.* neither iodine nor fluorescein had arrived as far as the observation well. It is

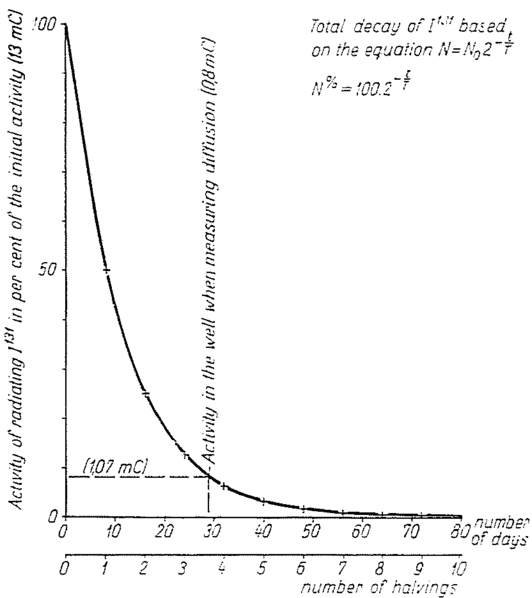

Fig. 9

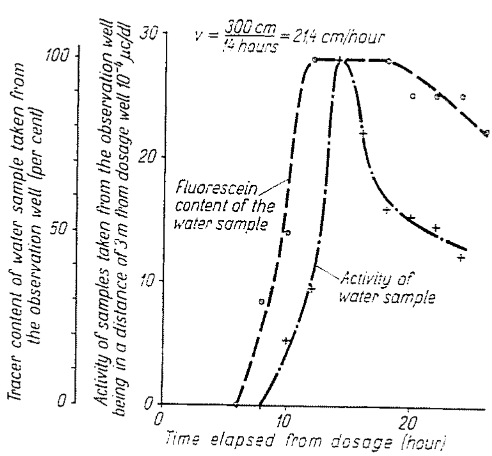

Fig. 10

most likely, that while drawing up the pipe liner, in the soil strongly disturbed caulkings and loosenings were developed, as a result of which flow conditions changed.

The measuring run with isotopes having ben completed, useful methodological observations could be made, summarized as follows:

1. Isotopes used for measuring as tracers are much cheaper as compared to fluorescein.

2. From isotopes considerably smaller quantities are needed for flow experiments, as a consequence, dosage can be carried out from tubes of smaller cross-section. When forwarding a tube of this kind to the depth required, soil structure will be less disturbed, thus the accuracy of measurements can be increased. The ampoule of isotope contents may be broken at an arbitrary depth.

3. When installing pipe liners of smaller thickness the preparatory works can be made much quicker and consequently more economically.

4. By applying thinner tubes, the soil structure being less disturbed, more observation wells may be placed around the feeding well, in that way not only magnitude but also direction of the flow velocity vector can be determined. Besides, as far as soil structure is concerned, also qualitative conclusions can be drawn.

5. Continuity of the measurings can be ensured and accuracy increased by means of special detectors placed directly into the observation well.

6. Features of the applied isotope are of such character as to cause no contamination danger if the method discussed is carefully followed.

7. The measurements can be carried out continuously as it is unnecessary to wait until the isotope in the well becomes entirely decomposed or — as *e. g.* in the case of fluorescein — the well completely cleaned out from the tracer. The radiation limit having been previously determined, the measurements may follow successively. Thus, measuring time can considerably be reduced.

In order to continue these measurements some technical problems are still to be solved, which, however, in our opinion can be realized without great difficulties.

5. Conclusions drawn from experimental results

As shown by the theoretical investigations [1], variations of the active discharge cross-section depend on the prevailing water pressure and gradient. Relying on this statement the usual assumption that flow velocity defined by the surface gradient may be generalized for the whole flow cross-section, is feasible but for aquifers of small thickness. Based on theoretical results, groundwater flow velocity is rapidly decreasing with the increase of depth when having a finer-grained aquifer and a small gradient. As to gravel and sandy-gravel layers, that decrease in velocity seems to be negligible.

On the other hand water household investigations [2] have pointed out, that even in case of sandy-gravel layers of great thickness occurring in nature, groundwater flow velocity is likely to decrease with depth. Experimental results seem to verify this, flow velocity decreasing with the depth below groundwater level — even in a permeable gravel layer — under the small gradient conditions prevailing in nature. As regards the sandy-gravel layer characteristic of the Little Hungarian Plain, at a gradient $I = 0.0005$, velocity slightly decreased until having attained a depth of 15 m, below that, however, it decreases rapidly. Below a depth of 25 m perceptible seepage could no longer be experienced.

Summary

The aim of investigations was to determine groundwater flow variations depending on depth by way of experiments at various depths of the soil. The measurements were carried out in a permeable sandy-gravel layer considered as homogeneous. For groundwater level observations 6 wells were drilled along a circle of 100 diameter. In the middle of this a dosage and an observation well were bored at a distance of 3 m from each other and following the gradient line. Fluorescein or active iodine could be fed at the required depth and the appearence of tracer observed at the same depth. As shown by the measurement results, flow velocity decreased while going deeper below groundwater level, namely in the following manner: down to a depth of 20 m rather uniformly, below 20 m to marked extent, whereas at a depth of 25 m practically no groundwater flow existed. Application of isotopes for measurements of this nature involves a great deal of advantages, the measurements being not so labour-consuming, more exact, more continuous and quicker, whereby considerable cost-savings can be achieved.

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