RÉALISATION DE L'EXPLORATION HYDROLOGIQUE DANS LA PROBLÉMATIQUE DE L'INFILTRATION ET L'ACCUMULATION ARTIFICIELLE DES EAUX SOUTERRAINES

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RÉSUMÉ

Lors de captages plus importants de l'eau souterraine des sédiments quaternaires il est généralement avantageux de compléter artificiellements les réserves de l'eau souterraine.

Les projets des infiltrations artificielles exigent (pour atteindre des paramètres avantageux) l'exploration hydrologique des éléments caractérisant le milieu filtrant. Dans cette contribution on vise à deux facteurs de base au coefficient filtrant k et à la porosité effective μ.

La grandeur du coefficient de filtration, des nappes, dans lesquelles la direction horizontale de l'écoulement aura en général lieu, peut être déterminée par les épreuves habituelles de pompage. Pour projeter une infiltration artificielle on a toutefois besoin de connaître principalement les coefficients de filtration sur le niveau de l'eau souterraine, dans le voisinage des bassins d'infiltration. Il s'agit de sa grandeur dans la direction verticale prédominante de l'écoulement. Dans ce but, on a examiné la méthodique des épreuves d'infiltration de l'écoulement permanent et non-permanent.

Pour faire le calcul, on a besoin de connaître la grandeur de la porosité effective qui influence essentiellement le calcul de l'accumulation possible de l'eau souterraine et de la vitesse réelle de l'écoulement. On présente la méthode de la détermination directe de la porosité effective et les résultats de quelques localités. Dans les résultats pratiques faits dans le champ on démontre l'influence du coefficient filtrant sur la durée de la rétention de l'eau dans le sous-sol, le procédé de l'écartement des matières organiques etc.

1. UTILIZATION OF HYDROLOGICAL RESEARCH IN PROBLEMS OF ARTIFICIAL RECHARGE AND ARTIFICIAL STORAGE OF GROUND-WATER.

For the solution of the problem of artificial recharge and artificial storage of ground-water can be used hydraulic and experimental hydrodynamic methods as well as the method of hydrological balance. Using any of these methods or procedures combining elements of various methods, the task of hydrological research lies mainly in the methodically correct derivation and application of basic parameters, i.e. the filtration coefficient "k" and the effective porosity "μ" which in each case provides a correct and economical design of the project.

2. FILTRATION COEFFICIENT AND EFFECTIVE POROSITY

Suitable hydrogeological conditions for artificial recharge as well as storage of ground-water are under central European conditions usually chiefly found in quarternary sediments, lining larger rivers in the form of valley terraces and lower terrace steps. In accordance with findings about the exertion of a greater driving force at the beginning of the sedimentation of these fluvial deposits, deposits of river bolders or coarse grained gravel-sands can be found on the bottom of the quarternary layers; in higher positions prevail fine grained gravel-sands and sands which in some places change towards the surface into eolic sediments, flood sediments etc. The hydrological result of this geological composition can be found in the fact that the layers on the bottom of the quarternary are usually the most permeable whereas the least permeability is exhibited by sediments near the surface of the area.

Infiltration reservoirs are situated in higher levels of the quarternary layers in order to get a sufficient gradient of the created ground-water table in the free horizon and to obtain the greatest possible water-bearing layer. The economic factor of the reservoir design and to a considerable degree also the qualitative effect of infiltration is dependent on the properties of the earths in these positions, chiefly on their permeability. The permeability of the rocks is important also for the whole farther space between the infiltration and drawing stations. On the permeability depends the retention time as well as further qualitative effects.

The effective porosity of water-bearing layers is fundamental for the determination of ground-water supplies and their changes under various hydrological situations. In the space above the ground-water table it serves for the evaluation of the future recharge of ground-water supplies after creating an artificial flow of infiltrating water. It permits also the computation of the attainable quantity of ground-water during the period of temporary interruption of the infiltration plant operation. When designing underground storage reservoirs as part of the artificial recharge system, the effective porosity is the basic characteristic for the determination of the retention volume (^{5}). It can serve as auxilliary quantity in the derivation of hydraulic parameters.

The values of the filtration coefficient of water-bearing layers are determined by pumping tests carried out according to known procedures. The method of determining the filtration coefficient of not-water-bearing layers and the methods of determining the effective porosity is substantially less elaborated.

When designing infiltration plants it is necessary to determine the permeability mainly in vertical direction since this flow component predominates in their vicinity. This is done by seepage tests. They can be principally divided into methods with permanent flow regime and seepage tests under non-permanent flow regime.

In the first case the seepage is most frequently measured from a circular cylinder buried in the ground. From the measured water quantity and the known area of the bottom, the values of the filtration coefficient can be calulated using Darcy's formula

$$k = \frac{v}{I} = \frac{Q}{FI} \tag{1}$$

where k is the coefficient of permeabilty, Q the seepage quantity, F the bottom area, v the filtration velocity, I the hydraulic gradient ($I = 1$).

In more precise measurements the effect of the spreading of the flow in porous media under the infiltration cylinder is taken into account. In the majority of cases this effect is eliminated by using concentric cylinders in which the same level is maintained. For the calculation according to the given formula, values determined in the inner cylinder are used.

These methods used mainly for purposes of increasing water-suplies are described in general hydrological literature.

In artificial infiltration research in the watershed of the river Jizera we decided to use large scale seepage tests with reference to the extent and costliness of the proposed project, especially in order to eliminate the difficultly enumerable effect of soil-mechanical factors such as capilarity, natural soil moisture, content of soil air etc. When preparing the test we started from the principle valid for laminary flow. I.e. that the shape of the flow area is not dependent on the magnitude of the filtration coefficient. A number of tests on a sand model of an infiltration well were carried out in the laboratory which proved that the shape of the surface in the environment of the well approaches spherical areas, until in sufficient depth (roughly more than 4 r of the well) the flow changes into the shape of a cylinder with the radius R.

In this depth the stream lines are already vertical and parallel. Hence with a gradient $I = 1$ the filtration velocity v is equal to the filtration coefficient. An increase of the depth in the infiltration cylinder causes an increase of discharge which is demonstrated by a spreading of the flow, which means in the case of maximum flow an increase in the value of R. Since for constant laminar flow, the condition of geometrical similarty is valid, it is possible to express the given relationship by the experimentally determined relation with dimensionles argumentss R/r and h/r, where h is the depth of the water in the seepage cylinder (Fig. 1). Using the known values h and r we determine according to the graph the value of R and the filtration coefficient we determine according to the formula (1) re-arranged to

$$k = \frac{Q}{\pi R^2}.$$

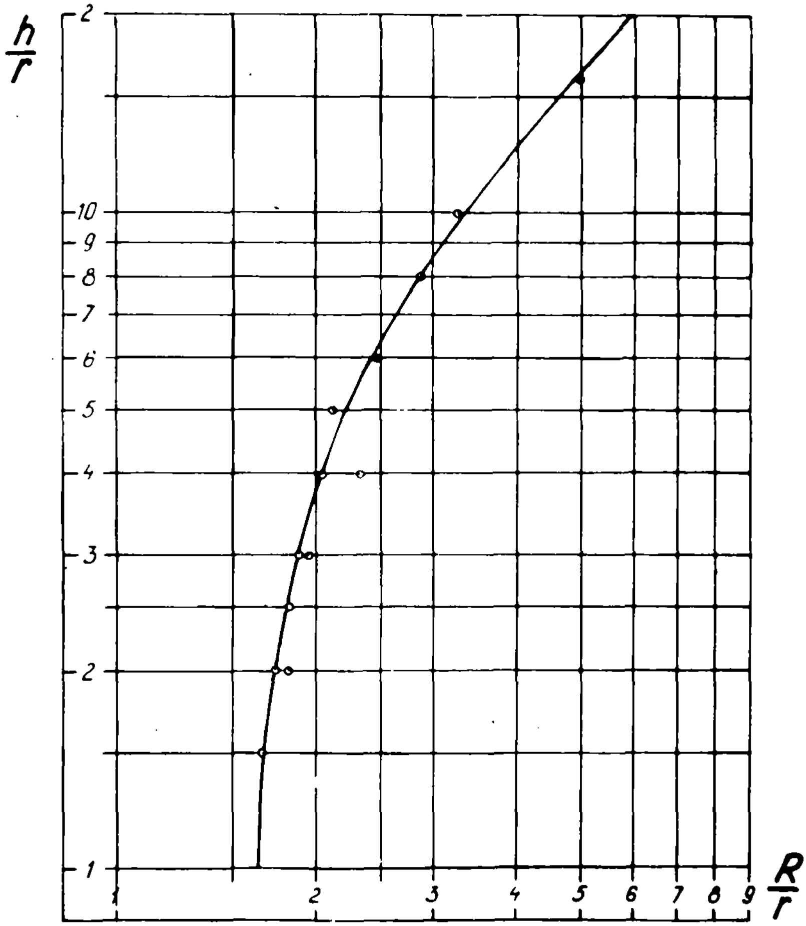

Fig. 1 — Relationship of dimensionless arguments R/r and h/r for the calculation of seepage tests under permanent flow.

After this analysis we evaluated long-term field seepage tests from six localities where the water infiltrated from concrete centerings with $r = 75$ cm. The average filtration coefficient found was $1{,}33 \,.\, 10^{-2}$ cm/s, with extreme values $8{,}45 \,.\, 10^{-3}$ cm/s and $2{,}16 \,.\, 10^{-2}$ cm/s.

To verify the methods we determined in two stations the permeability in parallel by seepage tests under non-permanent flow. These tests were developed in VVÚH, Brno (1) by analogy of a model filled with beads. The resultant formula is

$$k = \mu\frac{d}{t}\left(-0.15 + \sqrt{0.025 + 0.53\frac{h}{d}}\right) \tag{2}$$

where d is the diameter of the seepage cylinder, t the time necessary for the infiltration of the poured-in water, h the height of water in the cylinder immediately after filling, μ effective porosity.

In field measurements an unmeasured water volume is poured all at once into the cylinder buried in the ground, and its original depth is recorded and the time necessary for its infiltration measured. Knowing μ, we have all the values necessary for the calculation according to equation (2).

In our case we got $k = 1.18.\ 10^{-2}$ cm/s and $9.08.\ 10^{-3}$ cm/s, respectively. Thus the results showed a surprisingly good agreement of the two methods used and that the objections about neglecting the capillarity, temporary soil moisture, soil-air content etc. are not justified. In the calculation the values of effective porosity are involved which include the mentioned effects.

By the expression of effective porosity (μ) we understand here that part of the pore volume (n) which can be filled-in by the gravity ground-water in the earths. Hence we can characterize the effective porosity by the equation

$$\mu = n - \omega_0 - e \tag{3}$$

where μ represents the effective porosity
n the porosity of the rocks
ω_0 part of pore volume filled with bound water
e part of pore volume filled with air in the rocks.

The effective porosity can be also expressed as difference between the values of soil moisture beneath the free ground-water table and the level of capillary water. Numerically it is expressed in percentage of the total earth volume.

The values of effective porosity depend mainly on the earth-mechanical composition of the layers studied and on the moisture regime. With repeated fluctuations of the ground-water table the air volume in the pores changes to a small degree and together with it also the values of effective porosity. This depends on the changes of pressure, water temperature and air temperature. These complications in practice often lead to the fact that the values of effective porosity are usually only estimated or derived on the basis of other data found (grain-size, permeability etc.). However, data obtained in this way often differ greatly from actual values and would distort in our case the whole result.

E.g. earth of a certain grain size can have very different values of effective porosity according to the earth bulk density. We measured the effective porosity with gravel-sand with a natural density $\gamma = 2.07$ g/cm^3 and porosity $n = 21.7$ per cent. In the second test we prepared the same sample with a density of $\gamma = 1.97$ g/cm^3, $n = 27.7$ per cent, a third measuring was done with $\gamma = 2.14$ g/cm^3, $n = 19.1$ per cent. The resultant values of effective porosity μ were in these three instance 0,106 ; 0,120 ; and 0,070, respectively. Hence the extreme values are in the ratio 1 : 1,7 which is for practical calculations a considerable difference.

The mentioned example proves the necessity of obtaining values of effective porosities by direct measurements. This principle is maintained by using the method of determining effective porosity developed in the Hydraulic Research Institute in Prague, which combines elements of field and laboratory measurements. A dug sound of an earth sample is collected from the investigated layer (in which, e.g. the bottom of the infiltration reservoir is to be placed). During the collection the earth bulk density is determined using standard sand and from the collected samples the moisture of the material is found. Then 0,1 cu m of the same soil is transported to the laboratory and put into a test cylinder (Fig. 2) in single layers so as to obtain the original earth bulk density by maintaining the originally found volume weight. The sample is supported on a highly permeable gravel layer which is separated from the test material by a screen.

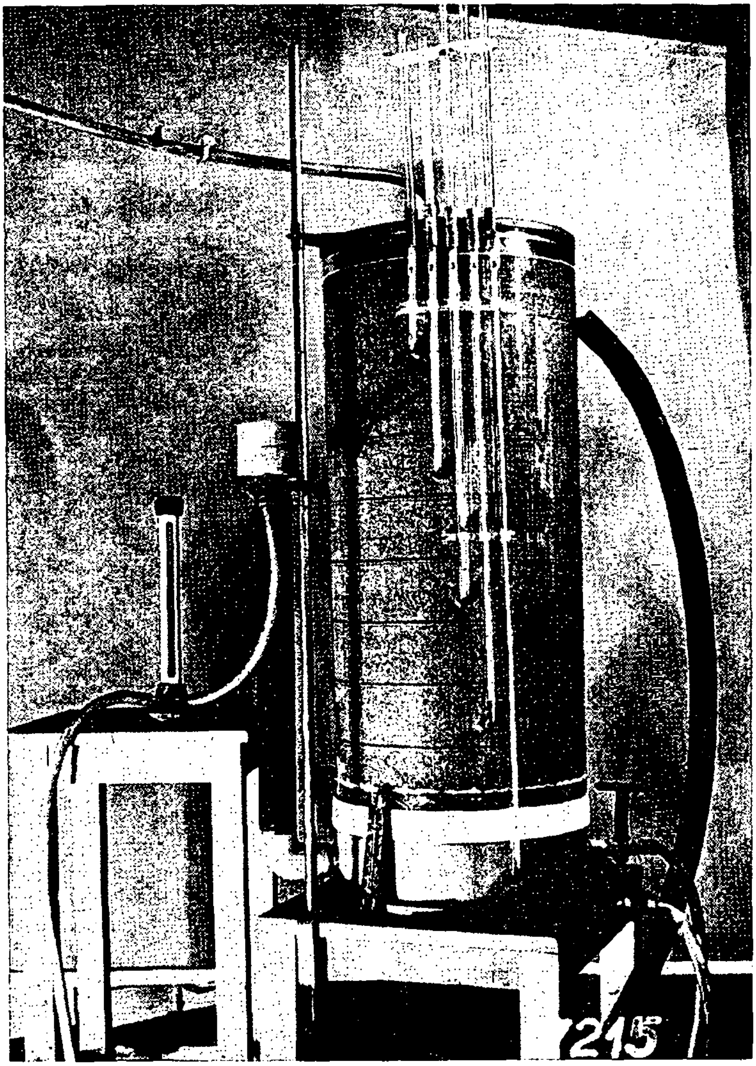

Fig. 2 — Apparatus for the measurement of effective porosity.

The amount of water added to the sample as well as the quantity collected and the fluctuations of the water table in the earth are measured in the apparatus. From this water quantity and the corresponding sample volume we always get the corresponding value of effective porosity. In the calculation of effective porosity we must, however, consider quantitatively the different soil moisture in nature and the moisture of the material compacted in the apparatus.

The apparatus permits the measurement of a 80 cm high sample. With material of low capillary height there is, therefore, between the low level (e.g. 2 cm above the basis of the sample) and high level (e.g. 62 cm above the basis) a sufficiently high earth column available. On the contrary, with samples of greater capillary height (e.g. about 40-50 cm) only a small rise of the ground-water table could be achieved

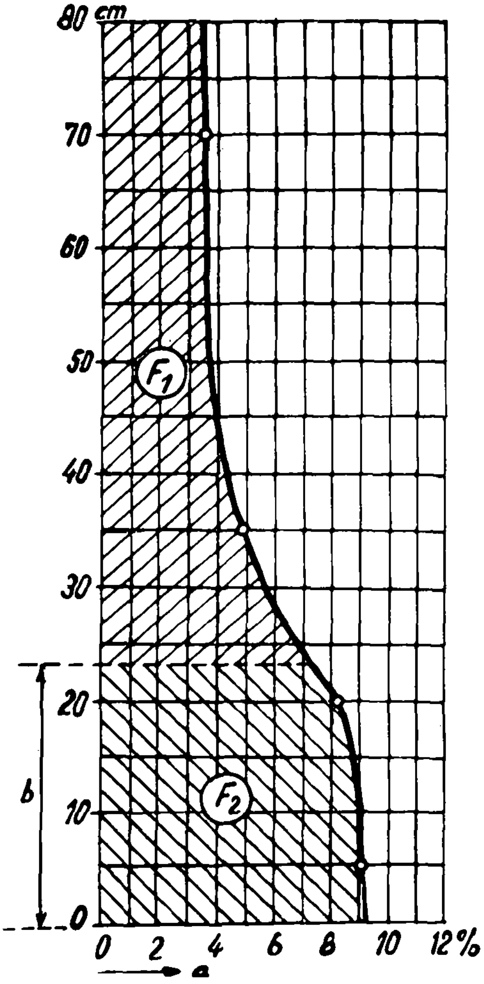

Fig. 3 — Soil moisture in various levels above the base of the sample after complete removal of water when measuring effective porosity (a — soil moisture in % of dry weight, *b* — capillary height).

with the whole capillary zone remaining in the sample. In such a case the surface of the sample is used as upper limit of the ground water table, the lower level must sink into the coarse material below the sample basis in order to equalize in the balance of supply and output the water quantity in the upper and lower capillary zone ([4]). When the water table drops below the basis of the sample, there remains a capillary residue in the lower part (F_2) of the cylinder (Fig. 3), which has to be eliminated quantitatively as excess moisture in relation to the average moisture of the zone F_1. On removing the water from the sample the necessary values of soil moisture in various levels of the sample are obtained by gravimetrical determination. Changes in the moisture regime during the measurements are recorded by electrical resistance measurement for which the calibrating curve is obtained using a cylinder of the same diameter with radially placed electrodes.

A method in wich the values of average moisture are treated quantitatively was used only exceptionally. To comply with the principle of direct measurement it is better to use the method using the registration of levels inside the sample for which no mathematical corrections are needed. With sands of finer grain it is, therefore, advantageous to measure the effective porosity in a higher cylinder with a smaller diameter consisting of flanged pieces.

The data obtained of effective porosity correspond to the actual state in the considered area (e.g. the artificial filtration plant) and can be satisfactorily used for the determination of the filtration coefficient. By combining methods of the seepage tests and measurements of effective porosity we get in an economic way satisfactory values of the filtration coefficient where pumping tests would not serve this purpose.

Pumping tests were also carried out in the mentioned localities. In the waterbearing coarse grained part of the filter layer, filtration coefficient values of 4 to 6. 10^{-2} cm/s were found. These data can be used with advantage in the calculation of collecting devices; however, in the design of infiltration reservoirs they would lead to considerably distorted results.

3. RESULTS OF VERIFYING RESEARCH

Verifying research in the pilot plant stage of artificial infiltration in the watershed of the river Jizera shows the necessity of detailed and methodically tested hydrological foundations for artifical infiltration. A syphon-system of collection requires here a practically equal lowering of the water table (Fig. 4.) along the whole length of the 500 m long infiltration reservoir front. The unequal thickness of the aquifer and variations of the filtration coefficients and effective porosity naturally cause substantial differences in the rate of the specific seepage and retention time of the water underground. The range of 18 to 43 days of retention and a specific seepage of 0,039 to 0,123 l/s.m seems in the relatively little differentiated horizon excessive. It is, however, necessary to proveit in time.

In places with the greatest specific seepage there occurs on the one hand the greatest clogging of the upper filtration layers and on the other hand, the substantially shorter retention time of the water undreground can adversely affect the quality of the collected water. To obtain an equal time of retention and in turn also a more uniform water quality would mean either to abandon the constant distance between infiltration and drawing objects or to change the gradient conditions in the different stations. Both ways are from building and operational reasons difficult to realize. Therefore, it is essential for even the most dangerous profile, in our case *D*, to meet the requirements as far as quality is concerned. However, as far quantity is concerned, it is the most satisfactory.

These conclusions are supported by the investigation results of self-purification processes between the infiltration reservoir and the collecting stations. In figure 5

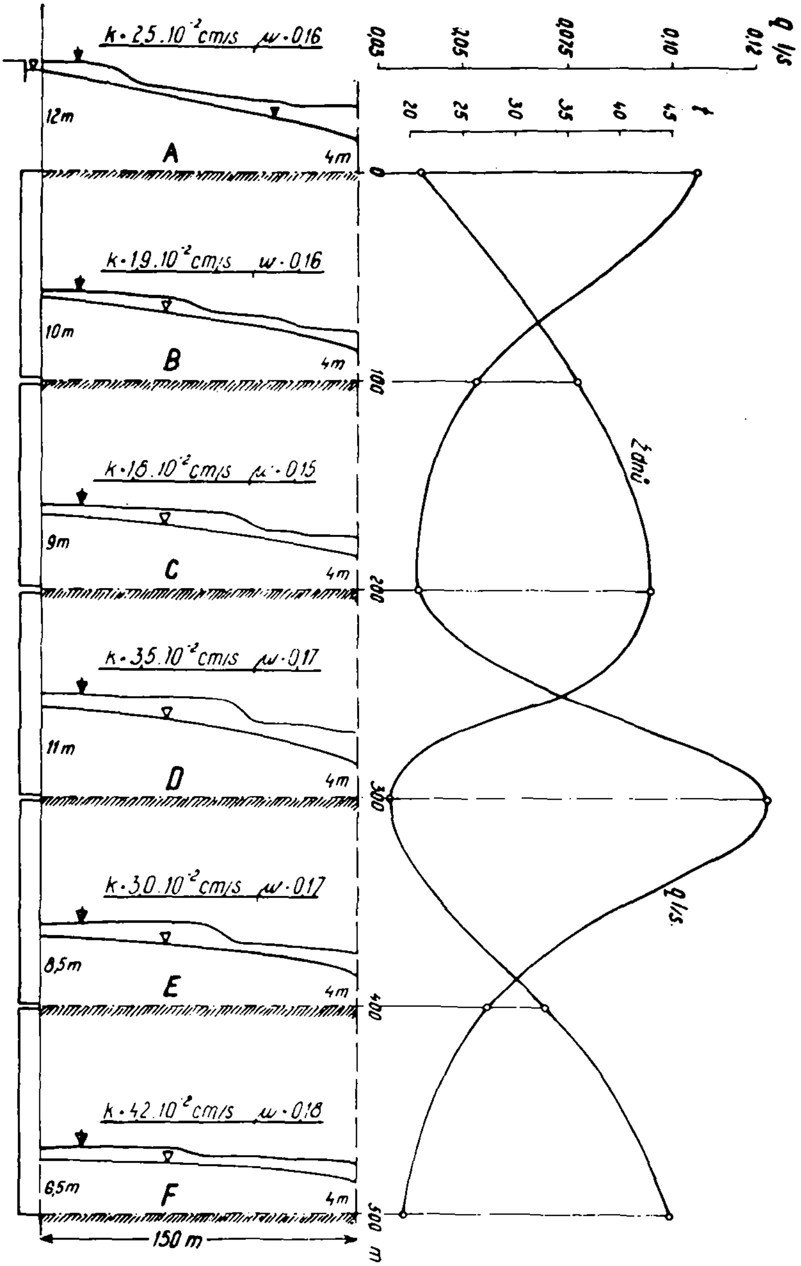

Fig. 4 — Example of the curve of specific seepages, *q* l/s.*m*, and total retention time *t* in days, using artificial recharge.

the curve of the removal of organic matter in a characteristical profile is plotted. The quantity of organic matter in mg O_2 in the infiltration reservoir, in control boreholes V_1, V_2, V_3 and the collecting well S are plotted on the vertical axis. The different curves show the course with various initial pollution of the water. From the curves it is evident that between the bore-holes V_2 and V_3 no purification takes place. This is explained by the existence of the old river-bed filled with coarser grained material with a permeability of $k = 9.28 \cdot 10^{-2}$ cm/s compared with the permeability in the sector V_1 — V_2 where $k = 4.48 \cdot 10^{-2}$ cm/s and in the sector V_3-S with a permeability of $k = 3.96 \cdot 10^{-2}$ cm/s (determined by the salt test). This relatively small sector with a greater permeability results in the given profile in the water not complying with the required quality. Compared with the idealized profile excluding the sector V_2-V_3 (the lower two thick lines) it would be necessary to prolong the filtration path roughly by 20 m in order to maintain the water quality.

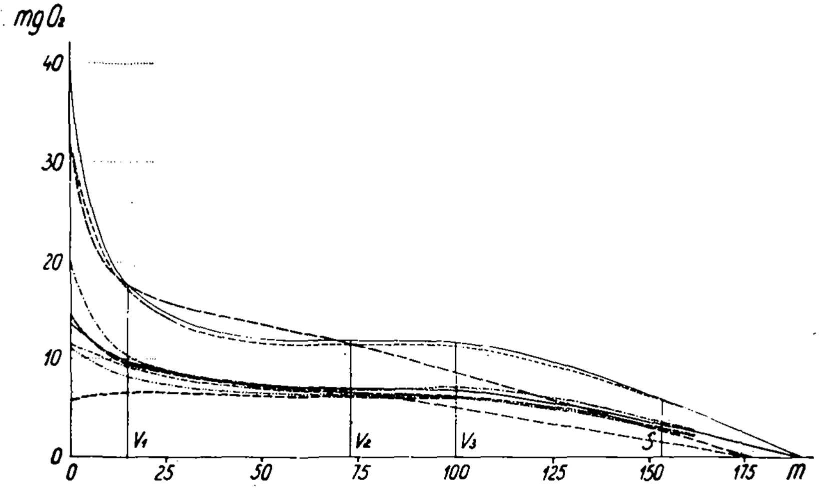

Fig. 5 — Removal of organic matter in a characteristical profile in relation to the length of seepage.

With heavy shock pollutions the river water, which is used for the artificial recharge, the performance of the infiltration reservoir is interrupted for a short time period. The water collection need not be restricted as long as there is a sufficient ground-water supply between the infiltration and collecting facilities. In the case represented in figure 4 there is between the highest operational level permitting complete collection an area with a volume of approximately 225,000 cu m. With an average effective porosity value of $\mu = 0.163$ there are 36,650 cu m of ground-water stored in it. With a daily collection of about 3,120 cu m this stored water quantity is then sufficient for almost 12 days. A mere three-per-cent error in the determination of the effective porosity value corresponds then to a two-day collection which means in the operational calculation for periods with great water shortage already an error of 17 per cent. These findings give a further example of the importance of methodically correct evaluations of the effective porosity and precise work during its determination.

4. CONCLUSION

Hydrological research plays an important role in the problem of artificial recharge in evaluating fundamental relations between the chosen site and its environment and for the design of the filtration stations proper. In the present paper the significance of methodically correct determinations and application of two basic factors for the design of artificial recharge — the filtration coefficient and the effective porosity — is shown.

Dimensionless arguments derived on models permit a simple application of infiltration tests with permanent flow regime. Consistent results are also reached by using the method of determining the filtration coefficient under non-permanent flow. This is possible by introducing effective porosity values obtained by using the proposed method into the calculation. In this way fully satisfactory results by a substantially more economic method are obtained. In addition effective porosity values found can be also applied in balancing of ground water supply and in the evaluation of possibilities of its storage.

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