Indian J. Met. Hydrol. Geophys. (1978), 29, 4, 629-642

556·3 : 628·1

Hydrologic investigations for water resources, water pollution and civil engineering operations using isotope techniques

U. CHANDRA*, W. DROST, H. MOSER and F. NEUMAIER

Institut für Radiohydrometrie der Gesellschaft für Strahlen-und Umweltforschung, Munich (F. R. G.)

(*Received 10 March 1977*)

ABSTRACT. A number of hydrologic studies for groundwater resources, water pollution and civil engineering investigations are reported. Measuring method and instrumentation developed lately are outlined. The field studies carried out in alluvials, covered investigations for comparison of borehole dilution technique and conventional pumping tests; groundwater supply to an industrial plant; installation of a well gallery for drinking water in a valley; determination of protection zone of a pumping site; pollution of ground water around garbage dumps and nuclear installations; construction of foundations; seepage from dams etc. The investigations carried in fractured and karstic aquifers included field measurements of, seepage rates of a dam built in basaltic aquifer; determination of inflow in a karstic well. The possibility of measuring vertical flow of groundwater even in borings in fractured or karstic aquifer has been practically demonstrated.

1. Introduction

For the last decade tracer techniques employing isotopes have been used increasingly for successful investigation of groundwater problems. The application of these techniques have shown that in many cases they not only confirm the results obtained by classical hydrological methods but as an alternative they provide more information and immediate answers to some hydrological problems (Feely *et al.* 1967; Harpaz *et al.* 1963; Drost *et al.* 1974; Drost and Neumaier 1974). The possibilities of application of these nuclear techniques for investigating water resources, groundwater pollution and groundwater problems in civil engineering are being reported. A description of the general techniques and the necessary instrumentation used during these investigations is also described.

2. Measuring methods and instrumentation

The measuring methods include single borehole techniques which are used for determining filtration velocity, direction of flow and vertical currents of groundwater in a boring. The applicability of these single borehole techniques depends on the knowledge of groundwater flow lines at the site of the boring. In alluvial gravels and sands, the laws of groundwater movement have been investigated in detail (IfR, GSF 1963-71; Halevy *et al.* 1967), but on the other hand water movement in fractured and karstic rock cannot be described by universal valid laws (Moser and Neumaier 1957, Mosetti 1960).

If a groundwater column of a borehole is labelled with radioactive tracer solution, the dilution of the radioactivity is a function of horizontal flow of groundwater through the borehole. The horizontal filtration rate v_f in soft rock after uniform mixing of the radioactive tracer can be expressed by :

$$v_f = \frac{\pi r}{2 \alpha t} \ln c_0/c$$

where r=internal radius of the borehole, c_0, c= concentrations of the tracer at time t=0 and t=t respectively, α=correction factor for flow line distortion due to the presence of borehole.

Experimental and theoretical requirements for successful implementation of this method have been carefully worked out in the last decade (IfR, GSF 1963-71; Halevy *et al.* 1967). Using this method filtration velocities of about 0·001 m/day were detected in model experiments (Klotz and Moser 1969). The higher limits of velocity that can be measured are governed by Darcy's law of laminar flow and may lie in the range of 20-300 m/day, *i.e.*, within the range of velocities that can easily occur in coarse gravels and aquifers subjected to heavy loads (Klotz 1971).

*Waste Management Operation Section, Engineering Services Group, Bhabha Atomic Research Centre, Bombay, India

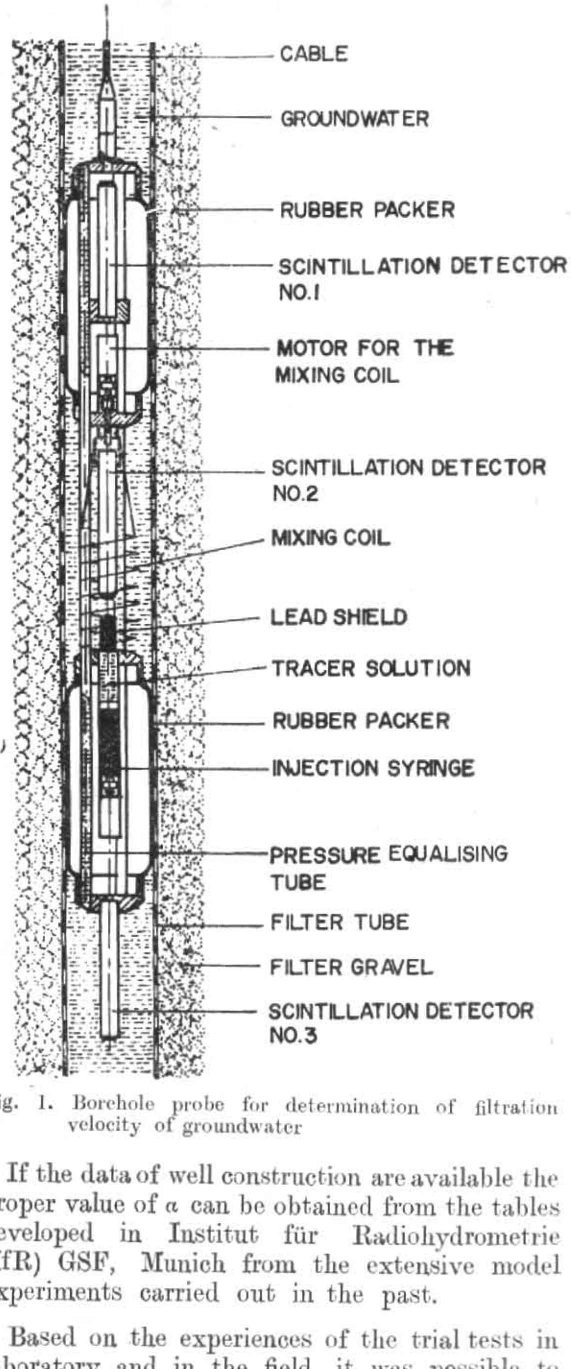

Fig. 1. Borehole probe for determination of filtration velocity of groundwater

If the data of well construction are available the proper value of α can be obtained from the tables developed in Institut für Radiohydrometrie (IfR) GSF, Munich from the extensive model experiments carried out in the past.

Based on the experiences of the trial tests in laboratory and in the field, it was possible to develop an improved borehole probe for measuring filtration rate. The probe, (Fig. 1) is of 7·5 cm diameter, 1·70 m length and is made of stainless steel and can be lowered in the borehole even up to depths of 200 m by one cable whose diameter is only 10 mm. The central detector is provided with rubber seals at both ends to avoid vertical flows. The upper seal also houses the upper detector and the motor for moving the mixing device consisting of a spiral wire. Below the central detector is the injecting device which is actuated by another motor housed inside the lower seal. The third detector projects downwards with its preamplifier unit housed inside the lower seal. A pressure equalising tube runs vertically through the length of the probe. Thus even after these measures, if some vertical or diagonal flows exist in the aquifer, they can be detected by the upper and lower auxiliary detectors provided for this purpose. In such a case the results of the measurements will have to be disgarded as a rule for quantitative estimates. It will then become necessary to measure the vertical water movements which are a function of filtration velocity and pressure distribution in the surrounding aquifer. To ascertain such vertical currents in boring, tracer logging methods have been developed (Drost 1970). These tracer logging methods, owing to the possibility of total count measurements and time measurements, yield more and precise information than obtained by conventional mechanical current meters.

For tracer logging a probe is lowered in the borehole at a constant speed. The radioactive tracer can be injected at specific depths or continuously over the borehole length. With pulse injection of the radioactive tracer the vertical throughput flow Q_v is given by :

$$Q_v = \left(v_l - \frac{s}{t}\right) q \, . \, k$$

In case of continuous injection the vertical throughput flow is obtained by :

$$Q_v = \left(v_l q - \frac{AE}{Rt} \right) k$$

where v_l = logging speed of the logging tool ; s = distance between the detectors ; q = cross-section of borehole; k=correction factor for effective cross-section for the vertical flow ; A=tracer activity continuously introduced during time t; E = detection sensitivity of the detector and R = count rate registered by the detector.

If the tracer cloud is recorded at time $t = s/v_l$ (ref. Fig. 2) the vertical velocity $v_v = 0$. If it is less than s/v_l, the vertical flow in the borehole is in the direction opposite to the movement of the probe. If it is greater than s/v_l the vertical flow is in the direction of movement of the probe. In this case v_l must be greater than v_v. Since it is difficult to fulfil this condition at high vertical flow velocities, it is convenient to log the probe in the opposite direction to the flow. A lower detection limit for measuring vertical flow velocity by this technique is given by movement of the tracer affected by diffusion while the upper limit does not exist.

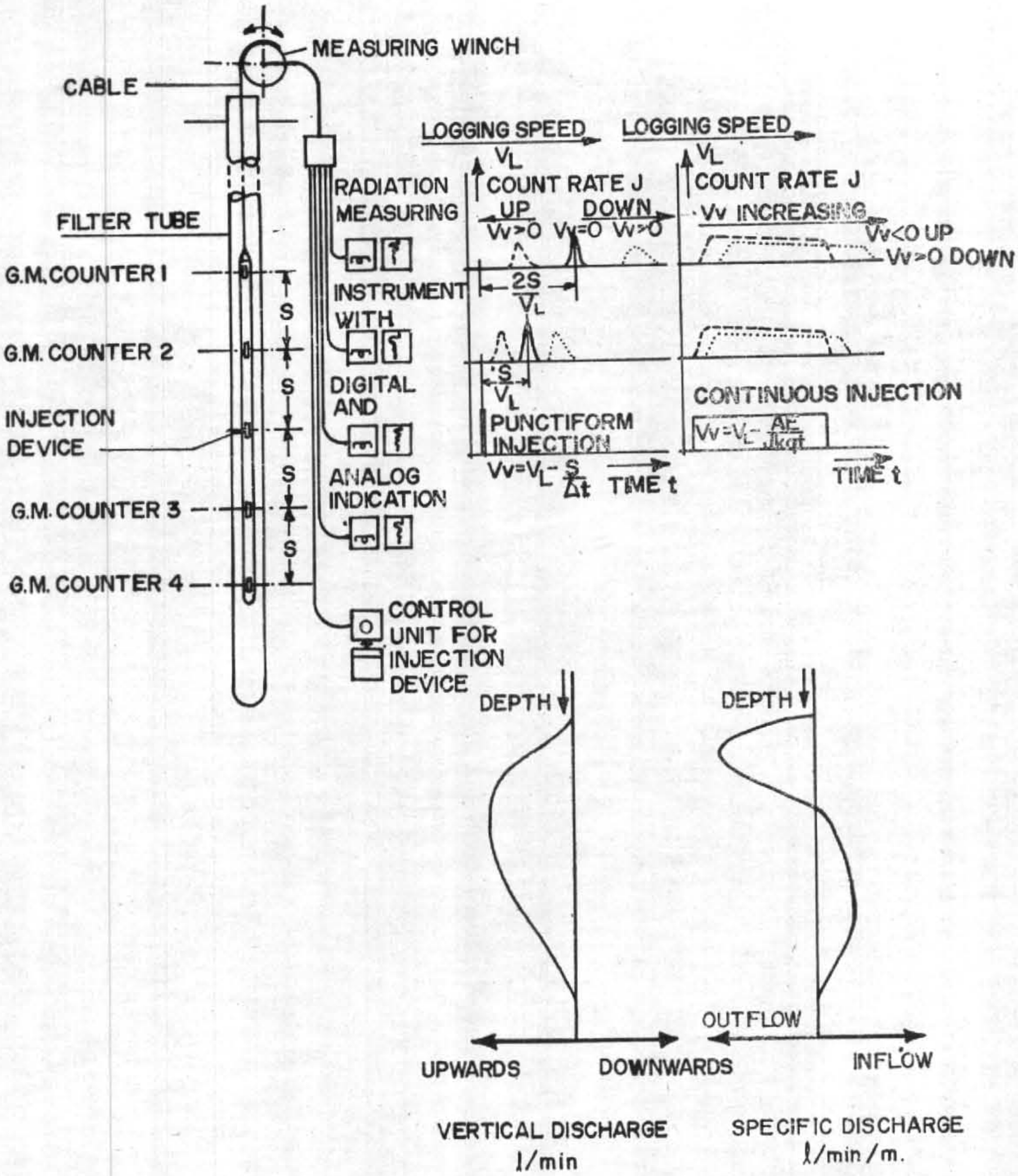

Fig. 2. Tracer logging and logging tool for determination of vertical throughflows in a groundwater boring

If the groundwater flow is disturbed by addition or removal of water, the borehole forms either a source or sink in the flow field. A similar situation occurs when artesian water flows through the borehole into another goundwater horizon. The intensity of the source or sink is a function of stream line density in the aquifer and is thus proportional to the filtration velocity (Drost *et al.* 1968) :

$$v_f = \frac{Q_v}{H} \frac{1}{b}$$

where Q_v/H = change in vertical flow Q_v in the borehole over the height H and b = width of the source or sink flow field in the aquifer. Since, usually neither the angle of inclination between the stream lines and the borehole nor the width of a source or sink flow field in the aquifer is known, the filtration velocity must be determined with sealed probes wherever the vertical flow commences or ceases. The v_f values obtained can be used as calibration points for the relationship between the vertical flow in borehole and the groundwater stream line density.

For performing the tracer logs the probe shown in Fig. 2 was developed. It consists of an injector for the radioactive tracer solution and four G. M. detector units. The injector which is electronically operated from ground consists of a syringe with 10 ml capacity. The detectors are fitted on either side of the injector at the interval of 50 cm. Because of its small diameter, the probe can be used for logging in borings with a diameter down to 3·75 cm.

If a radioactive tracer solution is carried away in the aquifer it becomes possible to measure its distribution by a directionally oriented detector. The direction of maximum activity corresponds to the direction of groundwater flow. The probe used for determining direction of groundwater flow is shown in Fig. 3. It houses a scintillation detector of 1·87 cm diameter and the probe has an overall diameter of 6·25 cm. The detector is provided with a collimated lead shield which can be rotated 360° northeast or northwest by a motor provided inside the probe. Square rods of 5 m length can be attached to the upper part of the probe for lowering it down to any depth. The injection of radioactive tracer solution is performed by the separate device shown in Fig. 4. It consists of a motor housed in a stainless steel casing. The lower end of the casing holds a syringe with radioactive solution. The forward motion of the rod attached to the motor presses the syringe and a constant injection of the radioactive solution can be carried out to any desired extent.

When applying these single borehole techniques, the groundwater boring should be equipped with a filter tube and filter gravel. It is important to ensure in the filter tube a water movement which is free from transport of sand or suspended matter. The filter gravel should be selected with respect to the aquifer in such a way that a correct grading of oversize and undersize materials is obtained. The filter tube should be such that its filter slot width is somewhat smaller than the undersized gravel fill. The permeabilities of the filter tube and the gravel should be considerably greater than the permeability of the aquifer. In fractured and karstic rock the measurement should be performed

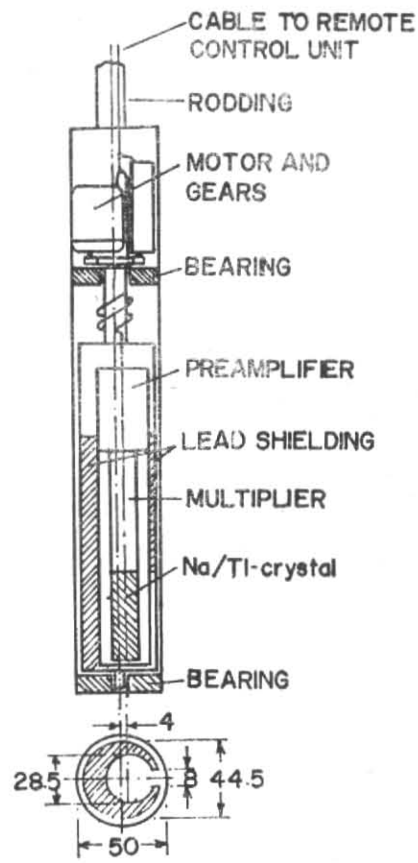

Fig. 3. Collimated gamma scintillation probe for determining direction of groundwater flow. Dimensions (mm), length of the probe, 600 mm

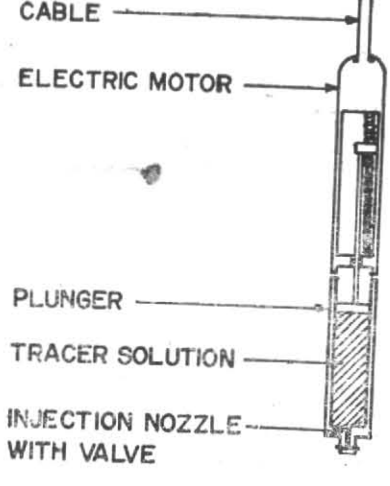

Fig. 4. Device for injecting radioactive tracer solution in the borehole

preferably in an undeveloped boring. The uniformity of the borehole construction can be confirmed by commonly used natural-gamma, gamma-gamma, neutron-gamma or neutron-neutron logging devices. The resulting logs along with temperature and conductivity logs help in identifying different water bearing layers in the aquifer and supplement the data obtained by borehole dilution techniques.

Among the various isotopes used in borehole dilution techniques (IAEA 1966), bromine-82 (NH_4Br-solution), iodine-131 (NaI-solution) and chromium-51 (as EDTA complex) have proved particularly suitable for determining filtration rates. These tracers are transported at the same velocity as that of the groundwater movement, since they are absorbed in the subsoil to a negligible extent. In earlier investigations these tracers were also used for determining direction of groundwater flow, but recently there has been increasing use of tracers like gold-198 ($AuCl_3$-solution) and chromium-51 ($CrCl_3$-solution) which are adsorbed in the aquifer surrounding the borehole. All these tracers can be injected in small concentrations ($\leqslant 10^{-2}\mu$Ci/ml), thus satisfying the general health and safety requirements.

Field investigations of Institut für Radiohydrometrie were carried out using mobile vans which were equipped with all the necessary equipment. By the improved battery operated and portable instrumentation used it has been possible to render field work less cumbersome, quick and easily reproducible. Most of the field work can be performed by a single person and this adds to the overall economics.

3. Field investigations

By determining filtration velocity, and if the gradient is known, the permeability of the ground water field can be obtained. These two parameters play a decisive role in solving problems of groundwater extraction, waste disposal and engineering geology. Ascertainment of direction of groundwater flow by single well method has become an elegant aid to the determination of, the drainage area of the groundwater field; protection zones for drinking water catchments; communication between two or more bodies of water and the load on the groundwater as a result of foundation, traffic and hydraulic engineering works. By measuring the vertical flows of groundwater in boreholes in soft rocks, in fissured rocks and in karst regions, it is possible to obtain data on piezometric conditions in the subsoil, aquifer anisotropy, water bearing horizons in the aquifer, the catchment area of a groundwater field and disturbance of groundwater flow by civil engineering operations.

Combination of hydrological data obtained by borehole dilution techniques and stable isotope measurements in local waters furnish excellent information concerning the groundwater flow in an area. The deuterium (D), tritium (T) and ^{18}O contents of groundwater samples from a particular region, in many cases, give precise clues with respect to stratification and origin of the particular groundwater (Davis *et al.* 1957; IAEA 1968). The D and ^{18}O contents can be routinely estimated by commercial mass spectrometer with an experimental uncertainty of $\pm 1°/_{oo}$ and $\pm 0{\cdot}1°/_{oo}$ respectively (Rauert Stichler 1974), while there exist many other satisfactory alternatives for estimating tritium contents in natural waters (Davis *et al.* 1967).

The investigations were carried out mainly in areas constituting alluvial gravel and sands but many measurements in fractured and karstic rock have also been performed.

3.1. *Investigations in alluvials*

An attempt has been made to compare the borehole dilution techniques and conventional pumping tests by systematic determination of permeability, the k_f-value by these two methods. The k_f-values were obtained by site tests during drilling while using a perforated cylinder introduced into the drill hole after withdrawing the pipes. The k_f-values were then ascertained by pumping or infiltration experiments. Altogether, 53 comparative measurements in the cylinder were carried out in the alluvial coarse gravels of Bavarian Lower Alps. The agreement between the pair of measured values was up to 85%. In 15% of the cases the difference was less than $\pm 10\%$, in 30% it was $\pm$(10-25)%, and in 35% it was $\pm$(25-50)%. In the light of this comparison and in accordance with the results from other pumping tests in alluvial gravel and sands in the south of Germany it can be said that the single borehole methods can produce substantially the same results as obtained from the usually very onerous pumping experiments. In addition to supplementing the pumping technique, the single borehole methods yield the stratification of the k_f-values in the vertical profile of a borehole (Drost *et al.* 1968, Drost 1971, Lohr 1969 a, 1969 b).

A groundwater supply from a 20 m thick aquifer for cooling system of an industrial plant in northern Bavaria was planned by releasing the effluent hot water downstream in the aquifer

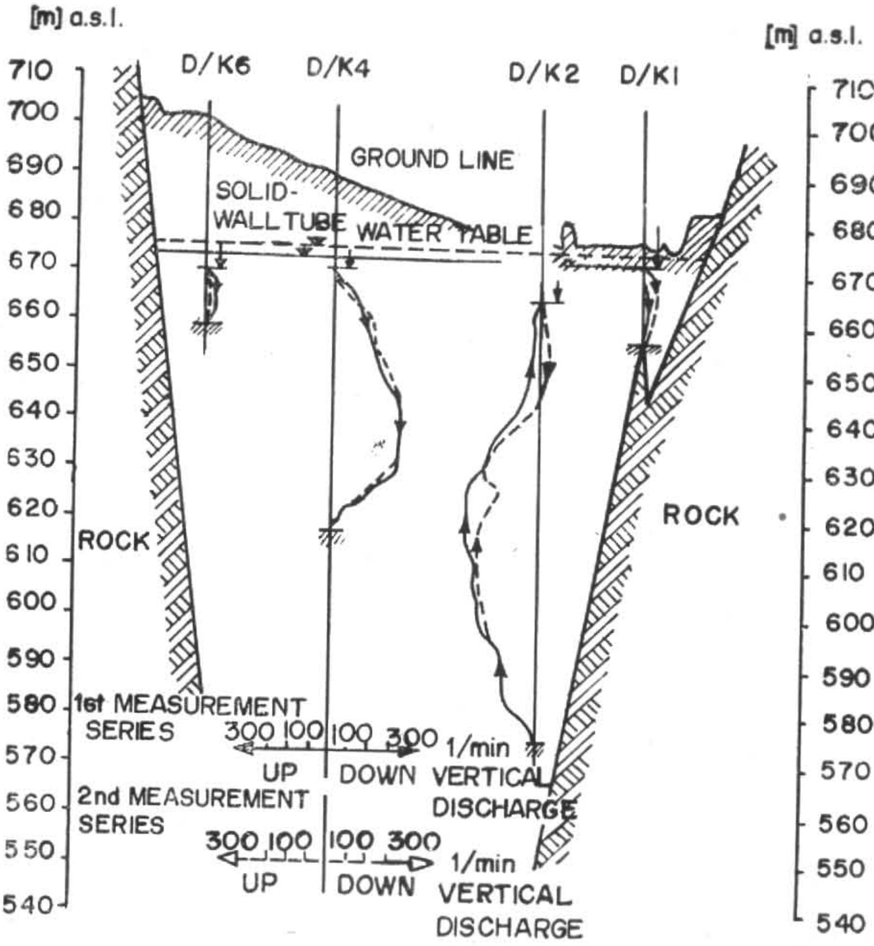

Fig. 5. Investigation of vertical throughflows by tracer logging in four groundwater borings in Loisach valley (southern Bavaria)

TABLE 1

Investigation of filtration rate, direction of flow and Deuterium contents of groundwater in Geretsried well, near Konigsdorf well (In the second series of measurements the Konigsdorf well was not operating)

Depth of measurement (m)	Filtration velocity (m/day)		Direction of groundwater flow (°NE)		Deuterium contents δD(‰)
	1st series	2nd series	1st series	2nd series	
2	0·25	0·15	320	200	—68·5
3	0·25	0·10	300	230	
4	0·30	0·10	280	240	—70·6
5	0·15	0·15	320	220	
6	0·15	0·15	340	240	
7	0·15	0·05	30	300	—71·7
8	0·15	0·05	40	320	
9	0·15	0·05	20	20	—72·0
10	0·15	0·05	10	20	

and pumping out the colder groundwater from an upstream site. The determination of filtration rates and direction of groundwater flow revealed (Drost, unpublished work 1973) that although there were no significant variations of filtration rates along the depth in the boreholes but the direction of flow in upper layers was distinctly different than in lower layers. Different directions of flow in upper and lower layers of the aquifer indicated definite possibilities of efficient thermal dispersion and local stratification of groundwater even in a homogeneous aquifer. The stratification, to some extent could also be due to induced flow towards a pumping station situated northeast downstream as it was tapping water from the shallow depths only.

In similar investigations near Königsdorf in southern Bavaria, the data obtained, Table 1, showed that filtration rate near the watertable was twice the value at the bottom of a boring penetrating only 10 m depth of the aquifer. Direction of groundwater flow also showed a distinct pattern of variation between the upper and lower layers, again indicating a stratification of groundwater streams rather than that of the aquifer. This finding was further confirmed by determining the deuterium contents of the water samples from upper and lower layers (ref. Table 1). The values near watertable are higher and correspond to the mean value of the surface waters in the area whereas the lower water with lower deuterium values was coming as seepage from hills. This typical hydrogeological situation seemed favourable for limiting surface water pollution in the area only to the upper layers of the aquifer whereas the deeper water could remain unaffected.

A well gallery for drinking water was installed in Loisach Valley, Bavarian Alps. The geohydrologic studies carried out in the past indicated the valley to be divided into two groundwater storeys. The second groundwater storey from where the water withdrawal is planned is fed by effluents from the rocky valley confines. To check these assumptions and to test whether in tapping the second groundwater storey a connection was established between the two storeys and whether the second groundwater storey received additional water from *Loisach* river, Fig. 5, single borehole techniques were applied in boreholes, 2 km upstream of the well gallery. The first measurement series were carried out during a yield pump test with a pumping rate of 3·5 m^3/sec and with discharge rate of 15 m^3/sec of the *Loisach* river while the second measurements were carried out without pumping and with 30 m^3/sec discharge of the river. The measurements included determination of vertical flows in these boreholes and filtration rates and direction of groundwater flow at surrounding points of the valley.

The results indicated a downward flow of groundwater along the edge of the valley and an upward flow in the centre of the valley. Inflow from the rock flanks of the valley was confirmed by the tracer method. Comparison of the two measurements series indicated that except for a few variations the results are almost reproduceable. The measurements indicated that the groundwater withdrawal planned in Loisach Valley does not affect very much the major groundwater flow conditions. In borehole D/K 2, a reversal of flow is evident in the upper range. In the course of second measurement series, groundwater flowed downwards at this point as a result of inflowing surface water of the *Loisach*. Inflow, however, occurs only till a depth zone that corresponds to the upper groundwater storey found at the site of the well gallery. This allows the conclusion that the storey separation, though no longer substantiated by this type of boring, is still effective. The inflow from rock flanks amounted to 300 l/min. The mean value of filtration rate measured in absence of vertical flows was about 4·1 m/day. Determination of groundwater discharge through the valley cross section yielded a value of 4·7 m^3/sec which corresponded to the value derived from classical considerations.

At a pumping site, it was assumed that water was being withdrawn from the bottom layers which consisted of highly permeable layers. Additional investigations carried out to determine vertical flows in the borehole by tracer techniques, revealed (Fig. 6) that water was coming from upper alluvial layers also thus indicating a much wider protection zone than revealed by boring and pumping data.

Studies of groundwater pollution with the help of radioactive tracers have been requiring special attention and priority elsewhere during the last few years. The garbage dump of city of Munich rests on detritus layers with a thickness of about 5 m, composed of sandy fine-to-coarse gravels. A direct contact between the garbage and groundwater does not exist. However, numerous temperature and conductivity measurements, chemical analyses and bacteriological tests (Exler 1972) have proved unmistakably that groundwater is affected with respect to its chemistry and temperature as it passes through the detritus under the garbage dump. It has been possible so far to follow the polluted groundwater front up to a distance of 3000 m from the dump disclosing that it spreads tonguelike in the general direction of flow (Drost 1973). Beyond the 3000 m zone the groundwater flows uniformly towards north with an average filtration velocity of 1·5 m/day. Within the polluted zone, most of the directions obtained vary from the main runoff direction and are also not consistent in relation to each other (Fig. 7). This is due to the fact that some observations wells are located at the edge of the polluted groundwater stream where the polluted water intermixes with colder and uncontaminated groundwater and thereby deviates within local limits from the general flow direction.

The immediate vicinity of nuclear energy installations are affected in a two fold respect: first, by waste heat from power generation and secondly by the normally practised release of radioactive effluents. Before the construction of Isar Nuclear Power Plant, Bavaria, tracer measurements were carried out to determine the filtration velocity, the permeability and direction of flow of groundwater. The tests proved that two groundwater storeys existed in about 8 m thick gravels. In the upper storey the filtration velocities registered fall within the range of a few metres per day and

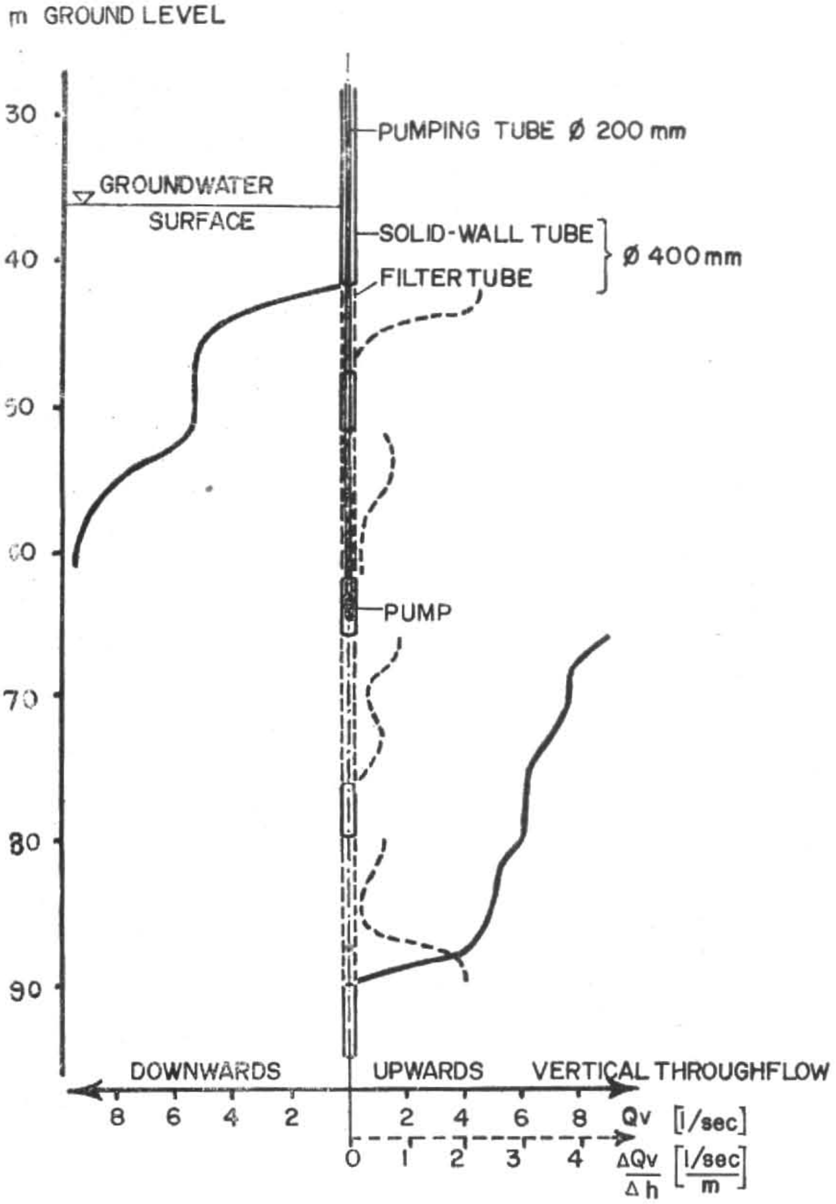

Fig. 6. Design of well and investigation of vertical throughflows and protection zone (withdrawal rate 20 l/sec)

the flow directions agreed with that determined by the hydrological triangle (Fig. 8). For the lower storey the filtration velocity values were smaller by one magnitude than those encountered in the upper and the flow directions deviated about 100° from those of upper storey. In addition, there existed a downward vertical exchange of water between the two storeys suggesting that piezometric pressure was higher in the upper storey than in the lower. From these findings it was possible to assess the spread of a possible contamination of the groundwater by released effluents and the intermixing of groundwater and the receiving stream of the *Isar* river burdened by thermal discharges.

Numerous applications of borehole dilution techniques in engineering geology investigations have been carried out by Institut für Radiohydrometrie, Munich. These investigations included planning of underground railway (IfR, GSF 1966, 1969, 1970), construction of motor traffic foundations (IfR, GSF 1969, Drost 1970), planning for a new airport (IfR, GSF 1969) and planning of barrages (IfR, GSF 1967, 1969). Borehole dilution techniques were helpful in recommending either of the two generally known methods of excavation, *i.e.*, open mining or horizontal drilling. In case of constructing foundations, the choice of removing the water either by pumping or by freezing is

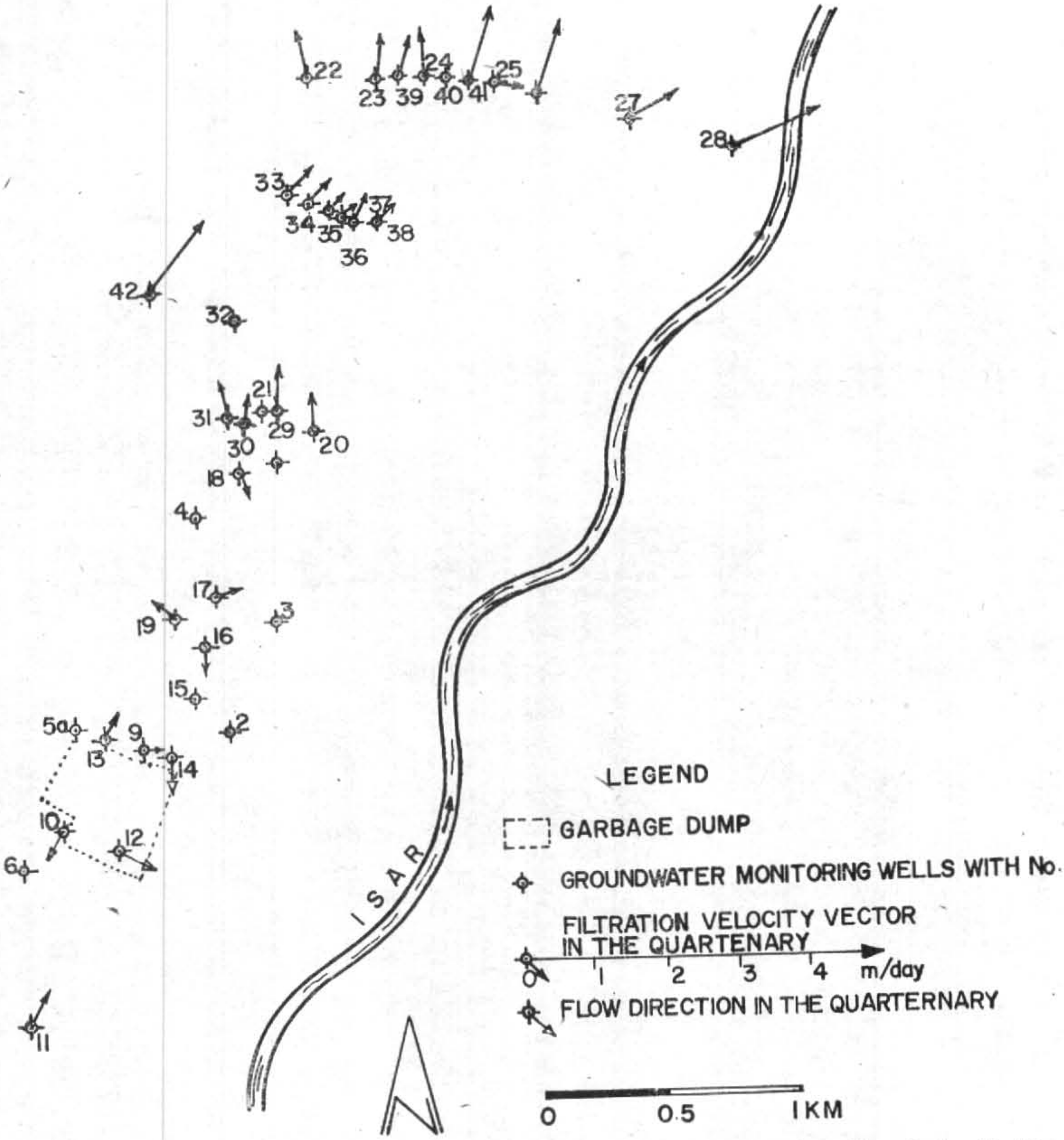

Fig. 7. Investigations of filtration rate and direction of groundwater flow at garbage disposal site, Munich

decided by filtration rates in the vicinity. Investigations at a construction site yielded filtration velocities of 1-3 m/day which were surprisingly high as the geology at the site consisted of fine-grained tertiary sands. Such high values are found where layers of alluvial marl have been found at the boundary of the underlying flint marl by erosive transport processes (Gebhardt 1968). Since these reworked layers could not be detected from the nature of the test bores, the contractor was thus provided with additional pointers to the nature and extent of dewatering operations needed.

Vertical flow measurements by borehole dilution techniques are particularly important in engineering geology. In the case of hydro-dams, water often seeps out underneath the impounding structure (Davidenkoft 1964). As a result groundwater streamlines run downwards on the upstream side of the dam and upward on the downstream side. Vertical flows will occur in any groundwater monitoring point in the neighbourhood of such a dam. The measurements of these vertical flows at Krun dam in southern Germany revealed the existence of such a seepage. In Fig. 9, this is reflected by the upwards vertical discharge at the downward

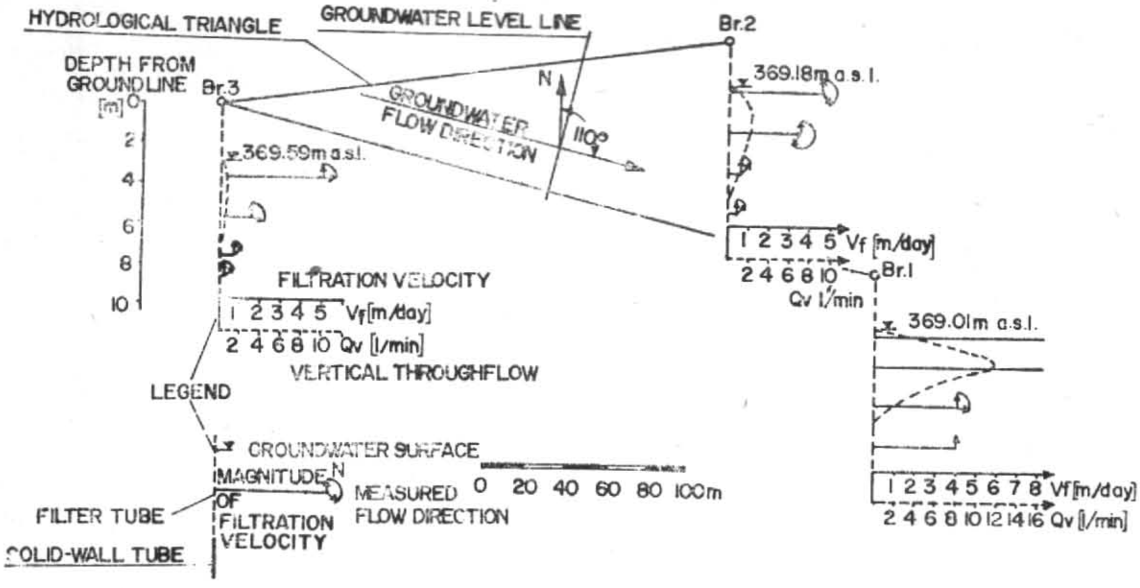

Fig. 8. Plan of groundwater borings Br. 1, Br. 2 and Br. 3 at Isar Nuclear Plant (Bavaria); profiles of filtration, velocity, flow direction and vertical through flows ; groundwater flow direction obtained by hydrological triangle

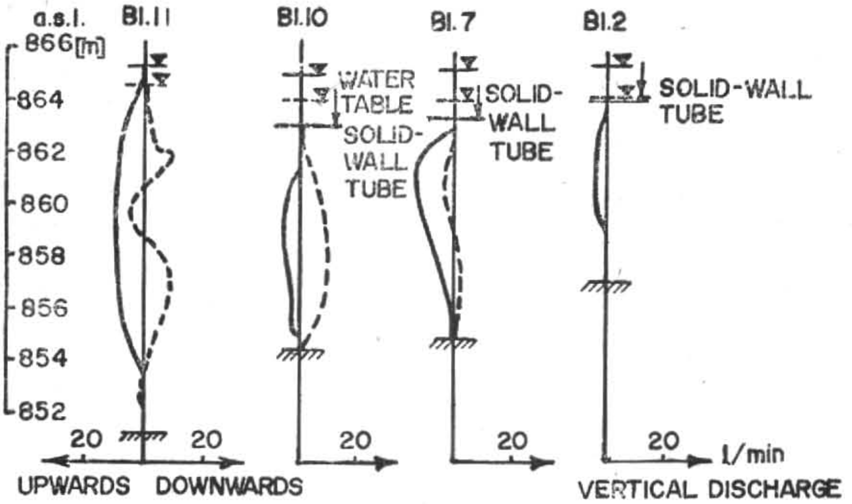

Fig. 9. Investigation of seepage in Krun dam in southern Bavaria
——— Vertical discharge curve before sealing
– — – — Vertical discharge curve after sealing

monitoring points. To stop this seepage, subsoil sealing by injection was carried out. The effectiveness of this measure is shown by the post-sealing discharge curves. It can be seen that upward component of vertical flow has almost entirely disappeared. The remaining groundwater movement is due to a harmless seepage around the dam on the left bank,

3.2. *Investigations in fractured and karstic aquifers*

In the light of the foregoing groundwater investigations, the single borehole techniques can be considered as reliable methods to determine quantitatively hydrological parameter in alluvial gravel and sands. On the other hand, in fractured and

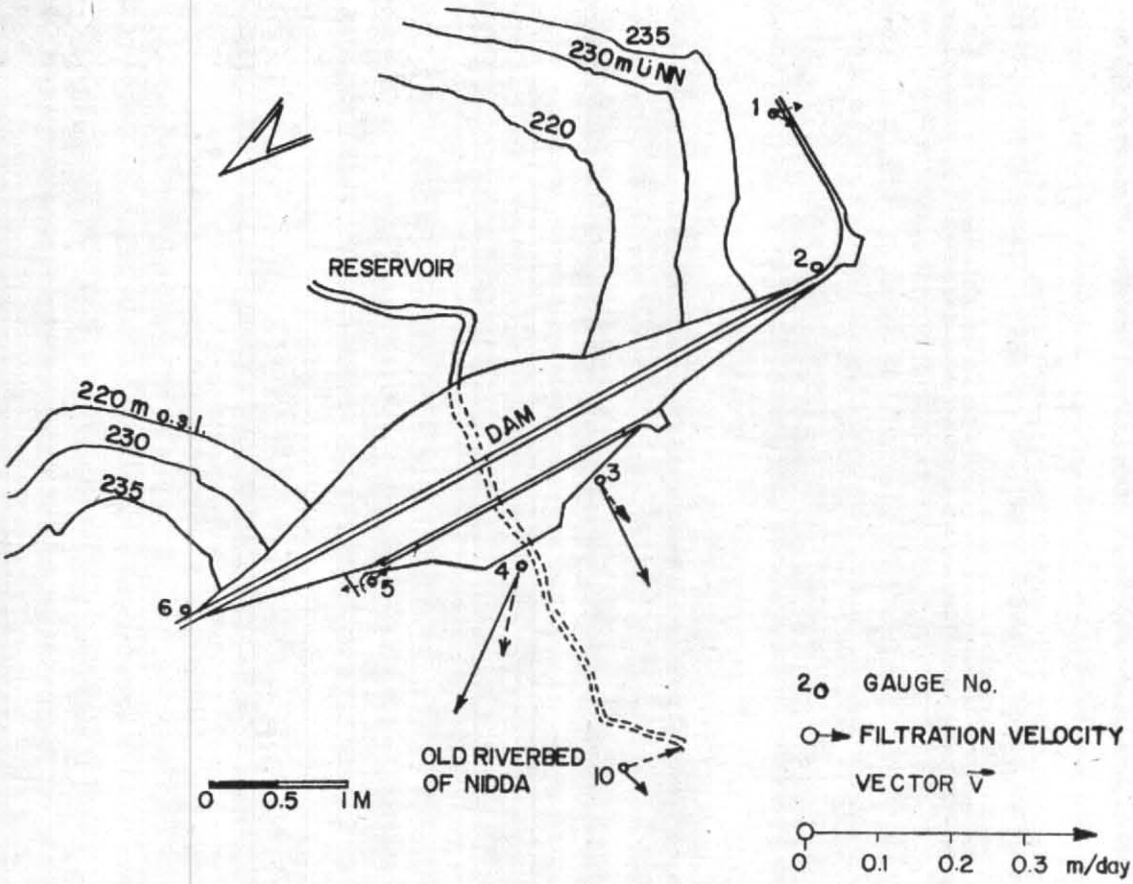

Fig. 10. Results of two series of measurements at the site of Nidda dam (Germany)
———→ Filtration velocity vector before cement injection at the base of the dam (storage level 210 m a.s.l.)
— — — — → Filtration velocity vector after cementation (storage level 226 m a.s.l.)

karstic rock the results of single borehole methods are utilizable normally only qualitatively because of the absence of a relation between the water movement in the boring and aquifer. But even relative values prove to be useful for correct interpretation. This can be shown by the following examples.

The foundation of the Nidda near Rainrod dam lies on a basaltic aquifer which is in part highly permeable due to the presence of fissures and caverns. Using single borehole techniques first series of measurements were performed in the network of the gauges at low storage (210 m a.s.l.). The results shown in Fig. 10 (continuous arrows) indicate high seepage rates near the old bed of the *Nidda* river. But this finding can be misleading while considering the anisotropy of the basaltic aquifer. A second series of measurements were continued at higher storage level (226 m a.s.l.) after the base of the dam was stabilized by injection of cement. The efficiency of this measure was confirmed by the results of the second series. At higher level of the storage of lower seepage rates were observed downstream of the dam. Comparing the results of the two series at the side of gauge 10, it can be seen that the velocity vector has turned to south, indicating an inflow to the aquifer at the downstream side after the injection.

Whether the well receives an inflow of subsurface groundwater was another problem to be solved during a pump test in Bavaria in a karstic well, standing under 10 m thick gravels in cavernous and fissured rock of the Jurassic period. The vertical flow movements in the well were measured by the tracer logging method. The measurement results shown in Fig. 11 reveal that no groundwater is being drawn from the surface gravels. Consequently, the protection zone for this well will be more confined than had the inflow from the gravels been present. The measurement results indicate that the well has two inflow horizons that exchange water when the well is not pumped. These results are demonstrating the possibilities of measuring vertical groundwater movement in borings in fractured or karstic aquifers. Under pumping

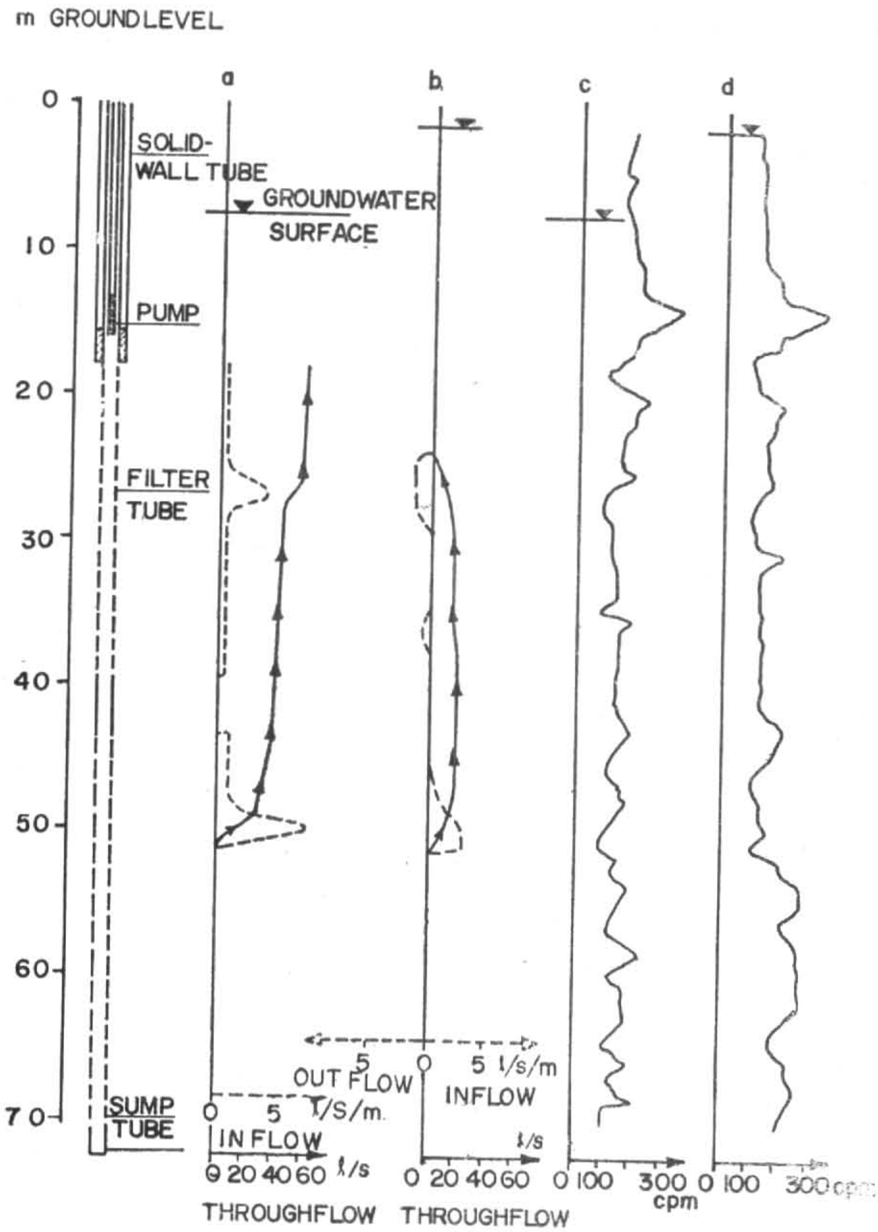

Fig. 11. Gammertingen well (Bavaria). Well design and results of single borehole measurements

(a) tracer log at a withdrawal rate of 60 l/sec

(b) tracer log without withdrawal

(c) gamma log prior to tracer log

(d) gamma log after tracer log (cpm = counts/minute)

conditions it is possible to determine the discharge rate of an inflow horizon quantitatively. Vertical water movement without pumping gives only some information about the pressure distribution in the aquifer and the location of water bearing horizons. Below a depth of 50 m, no water motion towards the well was detected. This result has been confirmed by two gamma logs in the boring: the gamma log recorded after the first tracer logging, Fig. 11 (d), has a higher radiation level below a depth of 50 m in comparison to the gamma log registered prior to the tracer measurements. This was due to the fact that the radioactive tracer solution added during tracer logging was incapable of flowing away. It is advisable, as done on many occasions, to perform such measurements before the boring is developed so that the results can be turned to advantage in equipping the boring, and avoiding, as was the case with Gammertingen well, a useless filter length for the lowest 20 m of the boring.

4. Conclusions

Borehole dilution techniques as supplement and alternative to conventional hydrological methods have been demonstrated to be reliably useful for quantitative evaluation of hydrological parameters. Most often the isotope methods yield much more detailed hydrologic information of an aquifer than the conventional methods. This has been demonstrated by successful investigation of variety of hydrological problems concerning groundwater resources, groundwater pollution and engineering geology in both alluvial and karstic aquifers. In fractured and karstic rock the results of borehole dilution methods are useful, normally, only quantitatively, but even relative results prove to be very helpful for meaningful interpretations.

Acknowledgements

The first author is grateful to Mr. K. T. Thomas, Director, Engineering Services Group, BARC and to Mr K. Balu, Head, Waste Management Operation Section, BARC for their continued interest and encouragement in the work and for giving the author the opportunity to work in Institut für Radiohydrometrie, GSF mbH, Munich under the guidance of Prof. Dr. H. Moser and Prof. Dr. F. Neumaier.

REFERENCES

Davidenkoff, R. 1964 *Deiche und Erddämme*, Werner Verlag, Düsseldorf.

Davis, G. H., Payne, B. R., Dincer, T., Florkowski, T. and Gattinger, T. 1967 *Isotopes in Hydrology*, IAEA, Vienna, 451-473.

Drost, W., Klotz, D., Koch, A., Moser, H., Neumaier, F. and Rauert, W. 1968 *Water Resour. Res.*, **4** (1), 125-146.

Drost, W. 1970 *Isotope Hydrology*, IAEA, Vienna, 421-437.

1971 *Geologica Bavarica*, **64**, 167-196.

1972 *Geologisches Jahrbuch*, Reihe C, **2**, 339-350.

1974 Water for the Human Environment, Proc. First World Congress on Water Resources, IWRA, **1**, 357-371.

Drost, W., Moser, H., Neumaier F. and Rauert, W. 1972 Eurisotop Office., Information Booklet No. 61, Brussels, 178 pp.

Drost, W. and Neumaier, F. 1974 *Isotope Techniques in Groundwater Hydrology*, IAEA, Vienna, **2**, 241-254.

Exler, H. J. 1972 *Gas-und Wasserfach*, **113** (3), 101-112.

Feely, H. W., Walton, A., Barnett, C. R. and Bazan, F. 1967 Isotopes Inc., USAEC Rep. NYO-9040, 340 pp.

Gebhardt, P. 1968 Die Geologischen und Hydrologischen Verhaltnisse beim Munchener U-Bahn-Bau, Dissertation, Universitat, Munchen.

Halevy, E., Moser, H., Zellhofer, O. and Zuber, A. 1967 *Isotopes in Hydrology*, IAEA, Vienna, 531-564.

Harpaz, Y., Mandel, S., Gat, J. R. and Nir, A. *Radioisotopes in Hydrology*, IAEA, Vienna, 175-191.

Institut für Radiohydrometrie, GSF 1963-1971 Jahresberichte.

REFERENCES (contd)

IAEA, Vienna 1966 *Guide to the Safe Handling of Radioisotopes in Hydrology*, Safety Series, No. 20, 39 pp.

1968 *Guidebook on Nuclear Techniques in Hydrology*, Tech. Rep. Series No. 91, 214 pp.

Klotz, D. 1971 *Geologica Bavarica*, **64**, 75-119.

Klotz, D. and Moser,, H. 1969 *Atomkernenergie*, **14**, 423-430.

Lohr, A. 1969(a) *Gas-und Wasserfach*, **110** (14), 369-376.

1969(b) Int. Water Supply Congr. and Exhibition, Special Subject No. 2, E 3.

Moser, H. and Neumaier, F. 1957 *Atomkernenergie*, **2**, 1-3.

Mosetti, F. 1960 *L'Energia Elettrica*, **37**, 781-797.

Rauert, W. and Stichler, W. 1974 *Isotope Techniqes in Groundwater Hydrology*, IAEA, Vienna, **1**, 431-443.