WORKING GROUP ON ISOTOPES IN HYDROLOGY

GRENOBLE OCTOBER 1965
FOREWORD

The purpose of this Working Group organised by the International Atomic Energy Agency, which met at the Centre d'Etudes Nucléaires in Grenoble by invitation of the French Atomic Energy Commission, was to provide an opportunity for the different groups engaged upon the use of isotope techniques in hydrology to discuss their present work and indicate the main lines of future work. In accordance with the decision of the meeting, members of the Section of Hydrology of the Agency have prepared this report based on written contributions submitted by participants of the meeting and on the discussions which took place. It is hoped that this report will be of interest not only to groups engaged in this work but also to hydrologists wishing to know what types of studies are in progress and where they are being carried out.
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1. FLOW GAUGING

1.1. Research Centre for Radiohydrometry, Munich, Federal Republic of Germany

Following earlier work on mixing lengths and minimum injection quantities the group has turned its attention to the measurement of flows greater than 100 m$^3$/s. Methods of enrichment of $^{131}$I have been investigated and discharge measurements performed on the Krüner Canal (17 m$^3$/s.) and Danube (640 m$^3$/s.).

The methods of enriching $^{131}$I include precipitation in the form of AgI and adsorption in the form of $I_2$ on ion exchange resins. The enrichment process occurs either continuously during sampling or afterwards from a water sample collected during the passage of the tracer. In the former case the volume of the sample is limited by the period of tracer passage and by the maximum processing rate.

In the continuous precipitation apparatus a constant flow of water from the sample is first treated, continuously, with fixed quantities of certain reagents: $H_2SO_4$ to prevent the precipitation of $AgCO_3$ and similar compounds and to achieve better flocculation; $NaHSO_3$ to suppress oxidation reactions which would otherwise interfere; $NaCl$, $KBr$ and $KI$ to provide an excess of precipitable material; and $AgNO_3$ to precipitate the halides. The sample is then fed into an agitator chamber with an adjustable time mechanism. From this chamber the silver halide precipitate is collected on a cellulose filter while the clear filtrate is drained off. After the passage of 600 l through this process the concentrated halides are extracted with about 2 or 3 l of Na$_2$S solution, dissolved in acetic acid and their activity measured in a well-type counter. The reduction in volume at this stage is about 200 l.

The authors reported difficulties encountered in laboratory and field tests which were due to the conversion of the small quantities of iodide added to the water, into a form which could not be precipitated. This form has not yet been identified. Another problem was the manner in which $I_2$ is adsorbed on suspended matter and its influence on the precipitation process. For future experiments a suitable co-precipitation process will have to be developed for $Br^-$. Reproducibility is still unsatisfactory due to the fact that AgBr is more readily soluble than AgI.

When the tracer is concentrated in the form of $I_2$ by adsorption on ion exchangers, water from the sample flows into a mixing chamber which continuously receives definite quantities of $NaI$ (carrier), $H_2SO_4$ (for acidification) and $NaNO_3$ (oxidizing agent). The liquid remains in this chamber for a period which depends on the carrier concentration and then is passed over a column filled with anion-exchange resin. The activity of the adsorbed iodine is measured, either in the resin or after elution, in a well-type scintillation counter. Elution is performed with a NaClO$_3$ solution which oxidizes the adsorbed $I_2$ and releases it from the resin. During oxidation of $I_2$ ionogenic iodine is produced which is partially bound to the resin by ion exchange. This can be removed by addition of $Na_2CO_3$ or $NaNO_3$. The apparatus used at present allows a throughput of 1000 - 2000 l per hour and per resin filling. The volume reduction obtainable in this way is roughly 500 - 1000 : 1. In river flow measurements
this lowers the detection threshold (and thus the minimum tracer require-
ment) by 1 or 2 orders of magnitude.

Just as in the precipitation process, there are difficulties in
the ion-exchange method as a result of the uncertain behaviour of $^{131}$I in
very low concentrations. Similar problems arise when the tracer has to be
prepared in a form which is adsorbable on soil particles, for measurement
of the direction of the ground water flow; or when predictions have to be
made regarding possible chemical changes in the tracer solution between
the injection and sampling points, for measurements in ground or surface
water. In order to study these problems and to test the radiochemical
composition of the injected solutions experiments have now started using
thin-layer chromatography which permits a quick separation and identifi-
cation of the degree of oxidation of the iodine.

The purpose of experiments made with dyes was to compare the tracer
dyes that could be used in hydrology with radioactive tracers. Data were
given for various dyes, obtained with a Turner Type III fluorometer.
(Table I, Columns 1-8). The detection threshold was taken to be the con-
centration of dye which gives a fluorescence signal exceeding 50% of the
background fluctuations and 1% of the most sensitive measurement range.
The temperature coefficient, $n$, was defined by the equation $F(T) = F(T_0) \exp n(T - T_0)$, where $F(T)$ and $F(T_0)$ are the intensity of fluorescence at
temperatures $T$ and $T_0$. The coefficient of photochemical effect, $m$, is ob-
tained from the equation $F(t) = F(t_0) \exp m(t)$, where $F(t)$ and $F(t_0)$ are
the intensity of fluorescence at times $t$ and $t_0 = 0$ when irradiation is
provided by a quartz mercury lamp.

Experience suggests the sulforhodamine dyes, particularly Sulfo-
rhodamine G extra, as the most suitable hydrological tracers for surface
water measurements.

The results the experiments made on the Danube and on the Krüger
Canal are given in Tables I - III.

1.2. Discussion

A question was raised concerning the factor of enrichment and the
tracer loss by adsorption, when dyes are used as tracers. A spokesman for
the Munich group replied that the group has no experience with enrichment
of dyes. As for the adsorption of dyes, Rhodamine, for example, was report-
ed to be subject to adsorption by sediments. Sulforhodamine G extra seems
to be a reliable tracer, but they did not have information at hand to ans-
er this question in detail. It was pointed out that Sulforhodamine B is
identical with Pontacyl Brilliant Pink B used by FEUERSTEIN of the Univer-
sity of California. In reply to a question concerning the efficiency of
precipitation and ion exchange methods of concentration and the effect of
the polluted waters on enrichment it was stated that recoveries in the
laboratory work were 100%, but some adsorption was observed in field
studies. In the recent canal experiments the precipitation method for en-
richment gave better results than the ion exchange method.

With regard to the mixing length it was stated that for a flow
rate of 450 m$^3$/s, mixing was incomplete even after 4 to 5 km. A comment
was made that different arrival times of the peak concentration were ob-
served in different points of the sampling section even after long distances and that good mixing is not defined by the simultaneous arrival of the pulse, but by the constancy of the time integral of concentration. If the areas under the concentration-time curves, at two different observation points, are not equal good mixing is not obtained.

During the discussions ANDRÉ of Electricité de France told of the measurement of a discharge of about 600 m³/s, using 60 kg of bichromate in 100 l of water. The measurement of bichromate concentration was made after reconcentration by reduction to Cr⁷⁺⁺ and adsorption. The distance between the injection and sampling sections was 6 km. Complete mixing was not observed even after 10 km.

The choice of the method was also a point of interest. GUIZIX explained that the amount of tracer needed for the point dilution method was less than the amount needed for continuous dilution method. For low flow rates the amount of tracer needed for the continuous injection method is at least twice that required for the instantaneous injection method. The ratio decreases as the flow rate increases and tends to 1.2 times to that required for the instantaneous injection method.

1.3. US Bureau of Reclamation, Denver, Colorado, USA

Canal flow measurements with radioisotopes have been under study and development by the Bureau of Reclamation since 1961. Field investigations have been made in several canals with discharges ranging from 300 to 8000 cfs. Included in these studies have been tests to (a) study and evaluate the basic mechanics of field applications of dilution methods including the gulp or total count method, (b) develop improved field procedures, and (c) perform flow measurements in irrigation project operations.

The results of these experiments, in general, were reported to be satisfactory and encouraging, with the difference of radioisotope flow measurements from operational values usually falling in a range of 5 - 10 %. It was also stated that with adequate mixing, discharge measurement accuracy of about 97 % or greater was possible. However, some situations had been encountered where the measured values were in error by as much as 20 % or more. These latter measurements were generally believed to be associated with non-symmetrical velocity distributions which had resulted in inadequate mixing. Present field procedures for selecting the points of injection and counting now include field study of the flow condition in the general region, where a measurement is to be made with a dye. Due consideration is then given to canal alignment and the presence of hydraulic structures which may enhance or inhibit mixing. Research work has included a study of tracer diffusion and mixing length. Results to date show that, surprisingly, only a small increase of mixing apparently can be achieved by multiple or subsurface injections of the tracer. This is discussed in the paper "Canal Discharge Measurements with Radioisotopes", SCHUSTER, Hydraulics Division, Proceeding ASCE, March 1965. (1).

Based upon the work to date it is believed that the basic method has been brought to a workable and useful state for canal flow measurements where moderate accuracies are required. Additional work is necessary to develop field procedures and techniques in order to realize the maximum potentialities of the method. Also, considerable investigations of tracer
dispersion and minimum mixing distances are required to define fully the capabilities and limitations of the method.

As yet, there is no fully satisfactory equation for obtaining a first approximation of minimum mixing length. The influence of multiple and subsurface injections need further field study. Using the analytical and field work in dispersion by Colorado State University and the Geological Survey, an equation, which appears to hold promise, can be obtained for estimating the minimum mixing distance. When applied to some of the data in SCHUSTER's paper, this equation gives a mixing length which is reasonably compatible with field experience. Additional tests should be made to test the validity of this and other equations for mixing length. Research work on canal flow measurements presently is being held on a stand-by basis in light of the current emphasis being placed upon tracer studies in reservoir leakage and turbine flow measurements.

The Bureau of Reclamation and Atomic Energy Commission are conducting a cooperative three-year development programme that seeks to devise techniques for using radioactive material to solve specific discharge measurement problems. The programme is coordinated with research in universities and with facilities of national manufacturers. Field tests of developed systems will be conducted in Colorado where the Bureau operates high-head turbines that are ideally suited for such tests. Final methods and equipment will be submitted to test committees for acceptance as standards.

The hydraulic phases of the research and development programme are directed toward an understanding of the fluid mechanics governing tracer mixing, sample introduction into the conduit and withdrawal of the sample from the flow. In many cases with turbines and pumps, the length of the closed conduit, available for radioisotope introduction and sampling, is short. Because the accuracy of the technique is highly dependent upon proper mixing of tracers, the investigation will determine the importance of such factors as the dispersion characteristics of the flow, the geometry of the conduits, injection and sample contracts systems, and the value of artificial turbulence.

Two test facilities are being used in the Bureau's Hydraulic Branch for defining some of the parameters of tracer injection, mixing and sampling. One of the facilities is an 8-inch pipeline, 90 feet long. Velocities up to 10-fps can be obtained for a study of the dispersion of tracer materials and methods of both injecting and sampling the tracer water mixture. This facility is in operation and data are being derived on velocity and tracers (dye and salt) distribution. A second facility is available for studying the injection of tracers into flows under a pressure head of 650 feet of water. This facility includes a high-head pump and cylindrical pressure cylinder for studying injection techniques as they are developed, designed, and constructed. Present studies from an 8-inch pipeline test facility indicate that for centerline injection into the pipeline flow, 55 or more diameters of pipe are necessary to produce adequate mixing of the tracer.

A study under subcontract is in progress with Colorado State University to determine the effectiveness of the natural turbulence of a developed velocity distribution in an 825-foot long, 36-inch diameter pipe-
to produce a uniform cross-section of diffusion of a tracer introduced from a point located upstream. The pipeline will be used to determine the minimum mixing distance to produce a maximum cross-sectional diffusion of the tracer.

Included in this investigation will be the development of procedures for introducing radioisotopes or other tracers into the pipe in such a way as to provide a maximum mixing effect. No results have been obtained from 36-inch pipe test facilities, but the study is in progress using dye as a tracer.

The portion of the programme emphasizing the application of radioisotopes includes a review of the best tracer for turbine flow measurements. A major portion of this particular study is to be carried out on a contract basis with a local university and will include investigation of such parameters as cost, physical and biological half-life, possible absorption by penstock linings and other surfaces, and counting efficiency.

New systems for injecting the tracer at an extremely precise rate under high heads are being developed. The method will be suitable for determination of flow by dilution, total count, and integrated sample techniques. The sample bucket technique will be used for tracer counting. A comprehensive scaler-recorder system is being designed for extreme accuracy with provision for automatic data output. This will be used either for data storage with punch cards or immediate data processing by hard wire communication with the Bureau's central computer facility.

The immediate programme is directed towards completion of a prototype system for laboratory testing and evaluation and initial field trials.

1.4. Discussion

The Danish group stressed the need for defining what is meant by "mixing length" and said that this problem should be treated from a theoretical standpoint and that this approach would be started by them. Attention was drawn to GLOR's paper, USGS Professional Paper 433 B (2), dealing with diffusion coefficients and prediction of concentration across the stream. It was stated that Electricité de France never had difficulties in estimating mixing length for flows up to 20 m/s and were using a formula where the mixing length is given by 50 times the cube root of the discharge.

1.5. Hydraulics Research Station, Wallingford, Berks., UK

To overcome the difficulty of determining the mixing length a method of proportional injection across the river was proposed. For this purpose an array of injection tubes uniformly spread over the section should be used. A volume of dilutant $\Delta Q$ (not necessarily the same at each point) is introduced simultaneously through each tube in a short time $\Delta t$. In general the time for the passage of the pulse through the measuring section will be long compared with $\Delta t$ and this allows the possibility of varying both $\Delta t$ for each injection point and, within limits, the phasing between the times of injection between points.

It will be clear physically and it can be also proved that after a long time, the amount of dilutant along any flow filament having a given
cross-sectional area is independent of the position of the filament in the cross-section. The result of having a constant value of the time integral of the concentration when \( t \to \infty \) does not depend upon the distribution of the dilutant across the injection section initially. However, to minimize the time (or length downstream) for this condition to hold, it is clearly necessary to introduce the dilutant uniformly over the section, \( \Delta q/\Delta z = \text{constant} \); \( z \) being measured across the width of the stream, in which case the time integral of the concentration will be constant \((0 < t < \infty)\).

In a similar manner, it can be shown that in the pulse injection method the time integral of the concentration is constant when \( t \to \infty \) irrespective of the initial conditions, and to minimize the length required for this condition to apply, the dilutant should be distributed across the section so that the integral will be constant initially. This condition will be satisfied if the dilutant is injected in such a way that immediately after injection the dilutant will occupy a slab of uniform thickness across the width and that the concentration across the slab is proportional to the velocity \((u)\). To do this, the quantity of dilutant injected across the section must be proportional to \( u \), the time during which the injection is carried out must be inversely proportional to \( u \) and the phasing between points must be arranged so that the injection at all points ceases simultaneously. (It should perhaps be remarked that \( u \) is intended to signify the mean velocity through the area increment with which each tube is associated.)

It might be objected that injection such as that proposed above presupposes a knowledge of the velocity distribution and hence the discharge, which is to be determined. However, only a rough adjustment would probably be sufficient to greatly reduce the mixing distance.

In practice it will not usually be convenient to inject at more than a few points across the width. For a channel in which the variation of velocity and depth across the width is small, the width of a cloud \( \Delta x \), dye released from a point increases approximately in proportion to \( x^{1/2} \), \( x \) being the distance downstream from the point. Thus the mixing distance \((L)\) is proportional to \( 1/N^2 \), \( N \) being the number of injection points. Evidently a considerable reduction in the mixing distance is theoretically possible by the use of a comparatively small number of points.

1.6. Discussion

The method proposed was discussed by several participants, the principal criticism being the difficulty of making an estimate of the discharge and velocities, previous to the measurement.

The approach of the Agency to the same problem was explained. The method consists of making a uniform injection across a section of the river, in a reach where the geometry of the river channel is rather prismatic (same condition as for current meter measurements) and take equidistant samples across a downstream section. In this case the formula for point injection method can be applied for each sample collected.

The distance between the injection and sampling sections should be as short as possible to minimize the interaction of longitudinal strips but
long enough to assure vertical mixing. An experiment was carried out in a tributary of the Salzach river (Austria), using inactive bromine which was later irradiated for measurement and satisfactory results were obtained.

It was agreed that the idea was worthy of study, although the difficulty of collecting several samples across the river and making a line injection was pointed out.

It was suggested that several isotopic methods used in stream gauging be subjected to a comparative and objective evaluation, possibly by the Agency.

With regard to the mixing of the tracer with the river flow the use of oil spreading of the tracer to achieve uniform mixing across the river was suggested.

Concerning the reduction of the mixing length it was stated that the arithmetic average of the concentrations of the samples collected across the sampling section gave satisfactory estimates, in the cases where the mixing is not complete.

2. SEDIMENTATION

2.1. Centre d'Etudes Nucléaires, Saclay, France

2.1.1. Labelling Techniques

Recent and present studies in the use of radioisotopes in sedimentation studies are concerned with the use of gamma emitting radioisotopes with relatively short lives, such as $^{198}$Au and $^{51}$Cr. The methods which are developed are directed toward labelling of sediments in the field where different problems exist for labelling sediments of different sizes.

In situ labelling methods are necessary when large quantities of sediments are to be labelled. The labelled material is deposited at the bottom of the river channel by using the Japanese method.

The low capacity of natural adsorption of sands and their low ion exchange capacity have led to different methods of fixation of the radioelement in the aqueous phase.

a) The radioelement in contact with the sediment is transformed into a colloidal insoluble form capable of being adsorbed by a layer of siliceous gel, which previously is formed or deposited on the sediment during laboratory treatment.

b) The radioelement is reduced in contact with the grain by an element (capable of donating electrons) which is deposited during previous treatments in the laboratory.

Essentially, these two methods are improved by the formation of a silica gel which is formed after the prolonged action of nitric acid and sodium hydroxide.
2.1.1.1. Labelling Sand with $^{198}$Au

The procedure which has been studied is a combination of those of PETERSEN (reduction of gold by tin) and CAMPBELL (reduction of gold by silver) which reduce the cationic $^{198}$Au to the elementary colloidal state.

The studies included:

- The previous deposition of silver under the influence of various organic reducing agents (e.g., hydrazine sulphate);
- The importance of the pretreatment on the fixation and especially on the strength of fixation. The decomposition of carbonates and the formation of an adsorbing silica layer are of primary importance;
- Influence of the origin of the sand (marine or fluvial) and its size distribution. The capacity of adsorption for a given sand decreases as the diameter increases. Fluvial sand (Loire), has for the same size group three times more adsorption capacity than marine sand (Dunkerque, Perpignan);
- The study of the degree of fixation has been made in model studies. At the present time it is possible to fix 20 Ci of gold per kg of sand, if the specific activity is 80 Ci/g. The efficiency of the fixation is 97%.

The loss is 0.8% for 9 hours in the case of a wave having the following characteristics:

- Depth of the water ........ 2.5 m
- Trough .................... 0.5 m
- Length of wave ............ 4 m
- Period ...................... 3 sec

2.1.1.2. Labelling of Sand by $^{51}$Cr (under study)

The formation of the colloidal chromium hydroxide on the surface of the sand particles has not been considered a suitable procedure. At the present time the chromium is deposited in the form of basic and colloidal lead chromate adsorbed on an arid silica gel which is formed by the hydrolysis of sodium metasilicate under heat and vacuum.

The difficulties arise from the slow adsorption of the lead chromate and of unsatisfactory fixation due to the fragility of the deposited silica gel.

2.1.1.3. Labelling of Simulators with $^{198}$Au (study completed)

The particles of polystyrene of density 1.042 have been labelled with a minimum modification of the parameters influencing the dynamic behaviour of the material and have resulted in a very good homogeneous labelling (relative standard deviation 9%).
2.1.1.4. Labelling of Silt

Adsorption is easier for silts due to their large specific surface, the presence of natural zeolites and the existence of substances in the colloidal and precolloidal state.

However, the chemical methods of labelling which modify the electrolyte concentration of suspended material cause the displacement of the equilibrium maintaining the natural conditions which keep the particles more or less dispersed. As a result a flocculation occurs, transforming the dynamic behaviour of the particles as the particles are finer.

Consequently, all the methods of fixation where the ionic concentrations are important cannot be used (for example the oxidation-reduction of gold at pH 0.5).

It seems at the present time that fixation at pH 7 of insoluble compounds with a large hydrated shell is less but not negligible.

The difficulty is then to distinguish the precipitated fraction adsorbed on the sediment from the precipitated fraction which is not adsorbed by sediments. For this purpose a method of differential filtration is used on filters of known porosity made of cellulose ester.

2.1.1.5. Labelling of Fine Material by $^{51}$Cr (study completed)

The chromium chloride is transformed into colloidal hydrate hydroxide at pH 7. The adsorption appears to be semi-quantitative for a concentration between $2 \times 10^{-3}$ and $4 \times 10^{-2}$ g/1 of chromium and 60 g/1 of sediment. It was shown that in this case the adsorption was a mass adsorption.

2.1.1.6. Labelling of Fine Sediments by $^{198}$Au (under study)

The chloride is transformed into an insoluble complex with a behaviour depending on the gold concentration and the age of the precipitation.

The studies concerning the influence of the concentration of gold on the dynamic behaviour are continuing.

These methods will be developed as a doctoral thesis and will be used for the labelling of sediments by other radioisotopes (Ba - La), (Zr - Nb), Ta, and Ir.

It is intended to study especially the modification of the dynamic behaviour of fine labelled sediments. This is the subject of a contract between the Laboratoire Central d'Hydraulique de France (LCHF) and the Commissariat à l'Énergie Atomique.
### 2.1.2. The Quantitative Estimate of the Bed Load Discharge

It is possible to have a quantitative estimate of bed load discharge by using the following approach:

The total number $N$ of counts per second recorded for a radioactive cloud representing the bed load movement is given by the integral

$$N = \int n \cdot ds$$

where $n$ is the number of counts for an elementary area $ds$ belonging to the radioactive cloud.

The bed load discharge is given by

$$Q = q \cdot l \cdot V_m \cdot E$$

where $Q$ is the bed load discharge, $q$ apparent specific weight of the sediment, $V_m$ the mean velocity and $E$ the depth of the moving layer.

$N$ is related to $E$ by the response function $f(z)$ of the detector with respect to depth and the distribution function $f'(z)$ of the tracer with depth.

$$N = \int_0^E f(z) f'(z) dz$$

If $f(z)$ is a linear function it is possible to demonstrate that the mean penetration depth of the tracer can be found irrespectively from the distribution function $f'(z)$.

Let $f'(z)$ be the concentration or activity of a radioactive sediment at a depth $z$, the mean depth is given by

$$z_m = \frac{\int_0^E z f'(z) dz}{\int_0^E f'(z) dz}$$

If we assume that the total activity embedded in a unit area is $a$, we have

$$a = \int_0^E f'(z) dz$$

Let us further assume that this activity is detected by a system of detection which gives a number of counts $f(z)$ for a unit activity in a unit area, embedded at a depth $z$. In this case the number of counts will be

$$n = \int_0^E f(z) f'(z) dz$$

if the system of detection has a linear response

$$f(z) = a - kz$$

"f," and "k" being constants depending on the characteristics of the instrument used and can be determined in the laboratory. The number of counts is therefore given by
\[ n = \int_{0}^{E} \Gamma(z) \left( f_0 - kz \right) dz \]
\[ n = f_0 \int_{0}^{E} \Gamma(z) dz - k \int_{0}^{E} \Gamma(z) z \, dz \]
\[ n = f_0 \cdot a - k z_m \cdot a \]

Using the above equation it is possible to determine "\( z_m \)" as "\( n \)", "\( f_0 \)", "\( k \)" and "\( a \)" will be known.

In general, in a problem of sediment movement the total activity "\( A \)" injected is known and the total number of counts can be replaced by the double integral \( \int n \, ds \) which, in its turn, is determined by the iso-activity curves. The equation thus can be written as
\[ z_m = \frac{f_0 \cdot A - \int n \, ds}{k \cdot A} \]

Detectors having a linear response function have already been developed for a depth of penetration of 10 cm for \(^{192}\text{Ir}\) and \(^{152}\text{Ta}\). Moreover, by using two detectors with different linear response functions it is possible to determine "\( z_m \)" exactly independent of the penetration effect. If more detectors with different response functions are used even more information can be obtained.

For all the hypotheses made concerning the distribution function "\( \Gamma(z) \)" it seems that the transport can be estimated within 25%.

If the response function is exponential as it is observed in experiments the discharge can be known as a function of a factor "\( B \)" which varies with "\( \Gamma(z) \), "\( f(z) \)" and "\( S \)". In this case if all the hypotheses are considered the discharge can be estimated with a precision of a few percent in the case of shallow depth of movement and within 30% for depths reaching 40 cm. The use of several detectors again brings in new information which increases the precision. At the same time it is possible to show that the use of two detectors also improve the application of the time integration method.

On the river Stung-Sen (1963), although the method was not fully developed the bed load movement was estimated to be 80 ± 20 tons a transport in agreement with previous estimates.

On the river Sienna, a coastal river in Cotentin, the bed load discharge during the period was estimated as being 21 ± 5 tons.

In this application a systematic study of errors, especially of errors which cannot be handled by computation was made: The way of representing the measures made in the field, the estimation of the mean count rate between the iso-activity curves. But these errors do not seem to be significant.

The method explained above is another way of interpretation of the results and requires no additional work in the field. Therefore, it is recommended to make an analysis of the count rates and use this information to estimate the thickness of the moving layer, and eventually to estimate the bed load transport rate.
2.2. US Bureau of Reclamation, Denver, Colorado USA

Sediment density measurements by gamma ray scattering. - An instrument developed through several years of study and field work in the Bureau of Reclamation is now being used in the Bureau's programme of reservoir resurveys. The purpose of the hydrographic resurveys is to develop new area capacity curves and predict future sedimentation patterns. This requires the measurement of the densities of deposited sediments. Incorporated in the field programme is also a study of the deposition, distribution, and physical properties of deposited sediments.

Field measurements with the gamma ray probe have been made at Lake Mead in 1963 and 1964, Boysen Reservoir, Wyoming in 1964, and Angostura Reservoir, South Dakota in 1965. The sediment density probe consists of a 25 mc cobalt-60 source and a geiger tube assembly separated by 16.5 inches of lead. A gravity drop is used and penetration of 40 feet into the sediment was obtained at Lake Mead working in water depth of 365 feet. At Angostura Reservoir, 20 feet of penetration was achieved. Little penetration was obtained in the sandy sediments at Boysen Reservoir.

Sediment densities from 1 to 60 pounds per cubic foot dry weight have been measured. The low densities are valuable in the study of the sediment interface and density currents. The results with the probe have been very promising and it is felt that the technique is far superior to core sampling. The gamma ray scattering technique is considered to be especially good for studies of sediment consolidation. Up to the present time little data have been available in this important aspect of sedimentation work. It has been found that there is little consolidation in sandy-type sediments, but several 100 % consolidations have been observed in silts and clays.

2.3. Wantage Research Laboratory, Wantage, Berks., UK

Three experiments made in an ebb channel, Firth of Forth, during 1961, 1964 and 1965 were described. (Full details of these experiments are given in AERE 4980 and AERE 5080). (6), (7).

2.3.1. The 1961 Experiment

During the experiment made in 1961 1.1 kg of radioactively labelled glass, ground to size match the natural silt were used as tracer. The total scandium-46 activity present in the tracer was 20 curies. The tracer was deposited from the deck of a drudge. The measurements were made by lowering the detection apparatus to the sea bed, and noting the count rate and the depth, using an echo sounder. Each point of measurement was fixed by the simultaneous use of two sextants which measured the two angles between three conspicuous points on shore, one of which was common to both angles. Measurements were generally made on traverses across the estuary to delineate the spread of the tracer.

From the individual daily measurements, the general pattern of movement of the radioactive tracer was obtained. It was assumed that the tracer is dispersed as a thin plane source. If the tracer is dispersed in depth, then this method of estimation will give too low a value and hence all results quoted are minimum values.
Results disclosed that an important part of the tracer released in the location called Oxcars Deep (a spoil area) travelled more than three miles upstream, to reach the dockyard in the ebb channel. Therefore, it was concluded that considerable recycling of the mud upstream was taking place without, however, any quantitative indication of the rate of movement.

2.3.2. The 1964 Experiment

During the experiment made in 1964 a hopper load of spoil was labelled and then deposited under normal operating conditions in the Oxcars Deep. The deposition was again at slack high water to obtain a minimum value for the upstream movement and to avoid problems of immediate upstream transport of suspended material.

Moreover, a horizontally collimated detector was constructed for examining the vertical distribution of the tracer in the silt deposits in the dockyard to provide a more accurate interpretation of the quantitative movement into the dockyard.

2.3.2.1. Preparation of the Tracer

Silt samples were again taken from the dockyard approaches and were treated with para-periodic acid and sodium perchlorate to remove organic material. Boron free glass was prepared containing 2.4 \% weight of scandium oxide with a density of 2.55 g/cm\(^3\) (about the same as the samples). Approximately 1,200 g were ground and size matched by sedimentation in sea water.

2.3.2.2. Detection Apparatus

A re-designed detector (ARD Type 1732) enabled a thin single-core armoured steel cable (0.11 inch diameter) to be used which allowed the detector to be lowered to the river bed in currents of up to 2 knots and enabled measurements to be carried out at all stages of the tide. The instrument was capable of measuring up to \(10^4\) counts/s.

2.3.2.3. Tracer Injection into a Hopper of Spoil

The tracer was injected into a hopper of spoil of 750 tons capacity, containing spoil having the consistency of liquid mud. Tests indicated that it had an average bulk density of 1.27 g/cm\(^3\). The seeding of the spoil by the tracer was made by crushing 39 ampoules which were uniformly distributed in the spoil.

2.3.2.4. Detection and Interpretation of the Tracer Concentration

Prior to the tracer deposition an extensive background survey of 100 points had been undertaken in the estuary and dockyard. As in 1961, the backgrounds varied between about 40 counts/s. and 80 counts/s. depending on the nature of the bottom.

As in the previous experiment the tracer cloud moved upstream, reaching the railroad bridge immediately downstream of the dockyards in one day. The cloud moved farther upstream during the days following the experiment, passing the dockyards an appreciable amount of tracer being deposited in the dockyards.
2.3.2.5. Vertical Distribution of Tracer in the Silt Areas of the Dockyard

To examine the vertical distribution of the radioactive tracer in the silt deposited in the dockyard a lead collimated scintillation detector was constructed. A collar of lead was located on the body of the detector and could be moved on mountings to give a "window" round the crystal of any required width. The choice of window width was determined by the conflicting requirements of detector sensitivity and vertical resolution. The value of 1 inch width was selected by lowering the detector through the plane scandium-46 source when the resolution (half peak width at half height) was 2.2 inches. Reduction of the window width reduced the counting efficiency without significantly improving the resolution.

The detector was lowered to the silt bed and allowed to sink through the active layer under its own weight. This was assisted by additional weights or by attaching 40 feet of steel conduit to the detector. To avoid trapping active mud in the window, this was filled with solid polyethylene. It was found that the mud was sufficiently soft to allow the detector to pass completely through the radioactive layer and hence to estimate its thickness.

The two investigations of silt movement from the Oxcars spoil ground using either 1 kg of radioactively labelled ground glass (1961) or a hopper load of spoil labelled with radioactive ground glass have shown the same qualitative result of extensive upstream movement. The results in 1964 were facilitated by the measurement of the vertical distribution of the tracer in the dockyard.

At least 30% of the tracer material was upstream of the deposition point 18 days after injection (1964), this forms a possible source of silt which can be transported into the dockyard either by upstream bed movement or as suspended material and may form a significant source of supply to the dockyard over a longer period than that examined in these investigations.

2.3.3. The 1965 Experiment

2.3.3.1. Choice and the Preparation of the Tracer

A boron-free glass was prepared containing 7% by weight of lanthanum oxide (La₂O₃). The density was 2.57 g/cm³. Approximately 550 g were ground, the median diameter of the ground material being 33 μm.

The amount of activity required for the investigation was approximately 40 curies. This would allow tracing to continue for at least 3 days and the tracer would still give a count rate equal to background if uniformly spread over 10 square miles at the end of this time. The previous investigations show there would be no health hazard in the estuary using this amount of radioactivity.

2.3.3.2. Detection Apparatus

The detection system comprised a scintillation head with a 2" by 1 3/4" dia. NaI (TI) crystal in a waterproof housing. This housing also contained an 3HT unit (AER type 1937) and was connected by 350 feet of single core armoured cable to a standard AER 2,000 series equipment.
operated from a 24 volt battery. The ratemeter would register count rates up to 10,000 c/s. The cable was 0.11" dia. with a surface coating of 0.025" polypropylene to prevent corrosion and was wound by hand on a small winch. A footage meter indicated the detector depth.

Before use, two detectors were calibrated using a plane lanthanum-140 source of known activity. The source was placed under water and each detector lowered onto it. From the count rate in contact with the source, the sensitivity of each detector was measured as 1 c/s per 7.1 x 10⁻⁶ Ci/ft². The stability of detectors during calibration and during field work was monitored with a cobalt-60 check source.

The procedure of tracer injection into the hopper of spoil was similar to that used in 1964.

2.3.3.3 Tracing of the Labelled Spoil

A complete survey was carried out the day following the injection and release of the tracer to the ebb channel. The tracer was located in an area extending 4 1/2 miles downstream of the deposition point with a maximum lateral spread of about 1 1/4 miles. A localised area of high activity 1,000 yds long and 200 yds wide remained in the channel to the seawards of the deposition point. This high activity area was estimated to contain a minimum of 27% of the injected material, interpreting the "off-scale" reading as full scale value of 10,000 c/s.

A more realistic interpretation, estimating off-scale as 15,000 c/s, would indicate 35% of the activity in this area. This interpretation assumes the spoil to be dispersed in a thin layer, and does not make any allowance for the depth distribution. Such an allowance would increase the percentage detected. Beyond this area a large "plume" of tracer extended, fairly uniformly in the seaward direction of the point of injection. This plume was of low activity and accounted for 35% of the deposited spoil. It is unlikely that this is distributed over any appreciable depth and the quantitative interpretation is fairly accurate. No upstream movement of tracer was detected although quite extensive surveys were carried out.

A second full survey which was carried out the fourth day following the release showed a similar tracer distribution as before. The highly active area in the ebb channel was significantly reduced both in size and in radioactive concentration (allowing for radioactive decay) and was now estimated to contain 14% of the injected material. The remainder of the plume seawards of the deposition point contained 34% of the tracer which was the same as the value measured the day following the deposition.

In addition, an area of activity was found to stretch upstream in the ebb channel for about 3/4 mile/and this contained 1% of the tracer. Two isolated patches of tracer each about 1/4 mile diameter were located at 1 mile and 2 miles upstream of the deposition point and contained a total of 1.5% of the tracer. The total tracer located was estimated to be 50% of the injected material.

A comparison of the results of the experiments made in 1961, 1964 and 1965 discloses the fact that deposition pattern from the channel shows a much more extensive downstream movement than that found at Oxears. The
"plume" spreading downstream from the localised highly active area contained about 34% of the deposited material in 1965 compared with 5% in Oxcars. Difference of patterns observed during the (D + 1) days is most noticeable when over 15% of the material deposited in Oxcars was upstream of the deposition point and spread in a continuous band as far as the railway bridge. At this time none of the tracer from the ebb channel was detected upstream of the deposition point.

2.4. US Department of Agriculture, Sedimentation Laboratory, Oxford, Miss., USA

The nuclear probes developed by PARAMETRICS INC. and IAEA to measure the suspended sediment concentration in rivers were described (8)(14).

The gauge of PARAMETRICS is designed for permanent mounting by the stream side such as from the bridge or a concrete structure at the river bank. The instrument consists of a small electronic instrument package (battery operated) which should be housed in a protected enclosure, and an underwater fish-shaped head which carries the nuclear source and the detector. The head weighs about 10 kg and may be supported either by a wire cable or steel rod.

The instrument must be visited at intervals of 7 days to replace the battery and the recording tape. Semi-continuous recording of sediment concentration is made (read-out at 15 minutes intervals). The sensitivity extends down to approximately 1,000 ppm the maximum being approximately 50,000 ppm. The radioactivity in the gauge is provided by a sealed source of cadmium-109 (ca. 2 mc).

The probe developed by the Agency is a portable one, and has the advantage of being coupled with a commercial scaler. The sensitivity extends down to about 500 ppm the maximum being 50,000 ppm with a 10% accuracy. The radioactive source used in the probe are cadmium-109 (ca. 2 mc) and americium-241 (ca. 100 mc).

It was pointed out during the subsequent discussions that the probes developed by PARAMETRICS and the Agency were complementary. PARAMETRICS' probe has a continuous record of sediment concentration at a given point of the river cross-section which might not be necessarily representative of the average concentration of the sediment in the river. It should be correlated to the average sediment concentration which can only be estimated by collecting samples across the section which precisely is the purpose of the probe developed by the Agency. It was mentioned that the Physical Electronics Department in Saclay was using a "Th" band for measurement of transport based on natural radioactivity.

2.4.1. Discussion

The question of the use of the sediment probes in the laboratory was raised and was answered to the effect that this is a possible but inefficient use of the probes. The IAEA probe is better adapted to this type of measurement.
The influence of the chemical composition and the size of the sediments on the measurements was brought to the attention of the working group. Calibration of the probes was carried out with materials of various origin and different particle sizes. The PARAMETRICS probe was found to be more sensitive to variation in sediment composition, but neither of the probes was found to be sensitive to the particle size. The Agency's probe gave the same accuracy down to a concentration of 500 ppm and the PARAMETRICS down to 1,000 ppm. The Saclay instrument based on the "Th" band requires "uniform conditions".

2.5. Some Further Considerations on Methods of Labelling and Safety Aspects

On the methods of labelling it was reported that quartz sand and ground glass were not good replacements for natural sand. It was added that experiments were now being performed in the Saclay laboratories about the dynamic properties of labelled sediments. The method used for labelling does not change the properties of silt-size material. With regard to the labelling of sand the aim is to develop a cheap method of surface fixation of the tracer in the field.

It was pointed out that surface tagging involves selective uptake by specific minerals and that labelled glass behaves as the silica fractions of the natural sand.

At Saclay it has been possible to correlate measured activities in surface labelling with volume rather than the usual surface area.

The question of safety in such experiments is complicated by the fact that different countries have standards differing by a factor of 1,000 or 10. The hope was expressed that the Agency should give an indication of safety limits for the isotopes involved: $^{48}$Sc, $^{192}$Ir, $^{60}$Co and $^{111}$Ag. It was replied that the Agency was at the present time preparing a manual on safe handling of radioisotopes in hydrology. Generally "RP" values are not practical for the beginning of an experiment. Experience is gained through experiments and quantities are usually increased when more information is obtained concerning the dispersion factors.

3. SEEPAGE LOSSES FROM RESERVOIRS

3.1. US Bureau of Reclamation, Denver, Colorado, USA

The use of radioisotopes is one of many methods presently under investigation and development by the Bureau of Reclamation to develop new or improved methods of field investigations which can be used early in the study of proposed reservoir sites. The data from the radioisotope investigation is a discrete and self-contained investigation; however, the results would be used in a greater overall interpretation using the results from the other studies now in progress. These include gravity meter surveys and infrared scanning. This provides a valuable opportunity for the correlation of the tracer studies with other results from an intensive broad investigative programme.
The objective of a tracer study will be pointed toward testing basic hypotheses of modes of reservoir leakage and obtaining the information which can help define any discrete areas of leakage in a reservoir. A medium size reservoir will be selected for the first tracer studies.

The first phase of the programme has been completed with the addition of 60 Ci of HTO to approximately 4,400 acre feet of water. This resulted in a concentration of 5,100 tritium units which is approximately 2% of the maximum permissible level of tritium in public waters. Over 100 samples have been collected for analysis. These were taken from the lake both before and after the addition of tritium, and from ground water in a drill hole at the shore. The future programme calls for determination of ground water flow at periods of different reservoir elevations, and a full-scale tracer programme during the summer of 1966 coinciding with a period of maximum reservoir elevation. This will include again tagging the reservoir with tritium, ground water velocity measurements at three drill holes located around the reservoir, and possible multi-tracer studies to explore water movement between drill holes. The field programme will be completed with a subsequent evaluation of quiescent ground water velocity measurements. The multi-tracer programme will be formulated as a result of the 1965 field tests.

3.2. France

The French group at Grenoble mentioned an approach, supported by an Agency contract, whereby the tracer is injected into a perforated tube closed at its upper end and which is immersed in the material constituting the bottom of the canal or reservoir. In this way migration and dilution of the tracer is avoided. A modification of this approach was reported to have been used in Poland, where continuous injection from the bank into a tube was made.

The use of neutron moisture meters for investigating seepage was discussed and a study in France was reported where three zones of seepage were located by finding areas of greatest humidity.

3.3. Spain

Study of seepage from a reservoir in Spain has been made using 16 Ci of 82Br to establish a connection between water filtering into a number of boreholes made along the slopes of the reservoir and water emerging at different points below a dam. For measuring highly diluted amounts of tracer, the latter was precipitated in 50 litre samples of water, as a result of which it was possible to detect concentrations of the order of $5 \times 10^{-9}$ Ci/litre. Also, cooperation with the IAEA the natural tritium concentration of water from different sources has been measured, on the basis of which it has been possible to postulate some preliminary hypotheses regarding water outlets actually due to leakage of the reservoir water. Completion of the study will still require several months of work involving further experiments on the interconnection of aquifers and the measurement of the direction and rate of seepage flow into the different boreholes. Experiments will also be carried out within the basin of the reservoir, to determine the actual extent of the seepage area. It should be noted that other groups have been carrying out seismic, electrical and geological exploration for the same purpose.
The use of stable isotopes of hydrogen and oxygen, i.e., deuterium and oxygen-18 was reported to be a useful tool for studying seepage from reservoirs. In the investigation made by IAEA in southern Turkey it was found that the lakes had significantly higher concentrations of deuterium and oxygen-18 than the precipitation and ground water in the same region. One of the purposes of this study was to determine some postulated relations between lakes situated at the southern edge of the central Anatolian plateau and the large limestone springs along the Mediterranean coast.

The deuterium concentrations of the lakes were found to be between -20‰ and -3‰ deviations from SMOW with a slight seasonal variation. On the other hand, all coastal spring disclosed concentrations which were almost constant and between -45‰ and -52‰. Therefore, it was impossible to support the hypothesis that any one spring in the coast was fed solely from the lakes in the upper plateau. It was first thought that the spring waters could be a mixture of lake waters and direct recharge in the region where the lakes are situated. But when deuterium concentrations were plotted versus oxygen-18 concentrations it was found that the spring waters could not contain appreciable amounts of water originating from the lakes, because the points representing the springs could not be situated between points representing the lakes and the precipitations.

It was also found that a spring in the same region reflected exactly the same isotopic composition as one of the lakes in the region which cannot be interpreted in any other way than a direct relation between the spring and the lake in question.

These results are encouraging in using stable isotopes in seepage studies from reservoirs and lakes. It should be born in mind, however, that the application of this method is likely to give better results for shallow water bodies or for reservoirs having large storage-inflow ratios.

4. HYDROLOGY OF SNOW AND ICE

4.1 Service des Isotopes Stables, Centre d'Etudes Nucléaires, Saclay, France

Investigations of isotopic relations in snow and ice have been in progress for several years over a broad range of subjects. Fundamental studies on fractionation during distillation were reported by MÉRIVAT et al. (2). Investigations of deuterium and oxygen-18 in lakes of the Great Basin were carried out by BORMANN et al. (3). Several investigations of polar and glacier ice were reported by BOTTER (4) and LORIUS (5).

Intensive investigation into the mechanism of the formation of hail has been carried out at Saclay. Since hailstorms are infrequent the samples must be preserved with care, particularly with no disturbance of the isotopic ratios. It was found that petroleum ether at -10°C made an excellent preservative.

An interesting correlation of the isotopic ratios in the several
layers of hailstones with the history of the stones in the storm cloud was presented by FACTY et al. \(^{(13)}\) and W.LIV.T et al. \(^{(14)}\).

The D/H ratios in the individual layers provide an indication of the temperature at which the transformation from liquid to ice took place and hence gives an indication of the altitude. Adiabatic conditions were assumed for the correlation of temperature with altitude and the assumption of 150 \(\times 10^{-6}\) D/H ratio was made for the original condition of the air mass. On this basis it is found that the hailstone formed around a nucleus at a relatively low altitude, was then carried by the storm updraft to higher altitudes (lower D/H ratio) in a series of irregular up and down motions. It is estimated that the maximum altitude attained was 5,500 metres. At this point the hailstone mass exceeded the lifting ability of the updraft and the stone fell.

The isotopic ratio of the successive layers was measured in the mass spectrometer by allowing the cold hailstones (of selected size) to slowly sublime and feeding the vapour into the instrument. The D/H ratio was then plotted against the decreasing radius of the hailstones. The bands of isotopic concentration established in this way were found to correspond with the structure of the hailstone as observed in a cross section under magnification. Another set of experiments was performed with bigger hailstones which were cut in small pieces of about 20 cubic millimetres. These pieces were then analysed by mass spectrometry.

The conclusions of these studies confirmed the first one, especially the fact that the stones were always formed in the lowest part of the updraft.

4.2. Institute for Meteorology, University of Innsbruck - IAJA

The application of isotopic techniques in glaciology through a joint project conducted by IAEA and the University of Innsbruck was reported.

The Institute for Meteorology and Geophysics, University of Innsbruck has conducted a research programme in glacial meteorology for many years. The glaciers of the Ötztaler Alps in southwestern Austria are the subject of study. Some of the glaciers have been under continuous observation for 70 years. An intensive programme of investigation emphasizing mass balance studies was set up in 1948 under Professor HOINKES.

The glaciers of the Ötztaler Alps result from snow accumulations at 3,500 metres and they extend to approximately 1,000 metres lower. The snow accumulation season extends normally from mid September to mid May. Ablation predominates throughout the rest of the year. One of the most thoroughly studied glaciers in the system is the Kesselwandferner which is equipped with 35 stakes in an area of 4 km. Totalizers are used to measure precipitation. Run-off from the glacier system is measured by recording stream gauge located 1.65 km from the lowest snout. The net accumulation of snow in a single season and the ablation of firm are measured through snow pits. The mass balance of the glacier is calculated from the relation:

\[ N - A - V = R - B \]
where \( N \) is the total precipitation, \( A \) the run-off, \( V \) the total evaporation, \( R \) the total net accumulation, and \( B \) the total net ablation.

In cooperation with the IAEA radioisotope measurements have been introduced into the study with the objective of dating the ice layers on the basis of the correlation of the radioisotope stratigraphy with the fallout history for the area. In 1963 samples were taken from a shaft 20 metres deep on the Kesselwandferner.

Sections were identified and tentatively dated according to the pollen stratigraphy. The total \( \alpha \) and \( \beta \) activity and \(^{137}\text{Cs} \) activity were determined for each section at the Österreichische Studiengesellschaft, Seibersdorf, and tritium determinations were made by the Tritium Laboratory, Section of Hydrology, IAEA.

The results of the determinations of \( \alpha + \beta \) and tritium are plotted in Figure 1. It is seen that a general, but not exact, correspondence exists between the two sets of data. The data show several anomalies. The fallout peak for tritium in 1958–9 is relatively low. The peak for the fall of 1955 appears to be misplaced as it should appear one year earlier in 1954. The tritium measurement representing the interval between the summer horizons of 1960 and 1961 is too high for this "test ban" period.

The most conspicuous anomaly is the very high tritium level found for the years before 1954. The lowest measurements in the layers representing "pre-bomb" era are 129 T.U. and 122 T.U. for samples indicated as winter 1953/4 and winter-spring 1952/3, respectively. These values indicate either a serious error in the interpretation of the pollen record or mixing between the annual layers. The latter seems to be the more probable as it is known that melting of the topmost layer takes place in midsummer. The possibility of mixing by vapour transfer must also be considered.

It is planned to continue the investigation using new core samples from different stations on the glacier. This may permit an estimation of the extent of mixing as a function of the microclimatology of the glacier surface.

5. MEASUREMENT OF VELOCITY AND DIRECTION OF FLOW IN BOREHOLES

5.1. Bundesversuchs- und Forschungsanstalt Arsenal, Vienna, Austria

5.1.1. Observations of Ground Water Flow Parameters and Development of Suitable Equipment

5.1.1.1. Development of Equipment

A new scintillation probe for filtration velocity measurements has been constructed which can be used in boreholes with a diameter of 3 to 4 inches. Additional simple devices allow measurements in boreholes with diameters up to 10 \( " \). By the end of this year a new 4 " direction probe for measurements in boreholes as deep as 300 metres will be finished. This probe will be operated with a special gyroscope. The second copy of this probe will be constructed with an outside diameter of 3 \( " \). The injection of the isotope will be performed by the special apparatus with the aid.
of which it will be possible to inject 0.1 ml of the radioactive solution in 3 seconds. As the total volume of the reservoir is equal to 2 ml it will be possible to perform about 20 separate injections without taking the apparatus out of the borehole. The apparatus has been constructed mainly for direction and vertical flow measurements and will be able to work with the direction probe or separately.

A new easy to operate water sampler has also been developed. The sampling chamber, except for the piston, is exchangeable and helps avoid any contamination if samples are taken from boreholes with high differences in tracer concentration.

The power to all probes, except the sampler, can be supplied by means of one cable which is placed on a small car trailer.

5.1.1.2. Some examples of problems which were solved by means of the single borehole technique:

At present $^{82}$Br is used for the filtration velocity measurements. In good agreement with MOSER's data, $^{82}$Br gives a final background in gravels and sands practically equal to the initial. For the direction measurements mainly $^{3}$H is used.

At a dam under construction at Groß-Reifling on the Inn River, seepage into the foundation was found. The water flowed through the soil along the river bed. Many boreholes were drilled there to locate and seal the most permeable zones (Fig. 2). Measurements of the filtration velocity by means of the point dilution method and of the direction by the single-well technique allowed the permeable zones to be localized. After sealing, the measurements were repeated in some boreholes in order to determine the efficiency of two kinds of seals that were applied.

Studies of the underground inflow to the Neusiedler Lake are in progress. Observation boreholes have been drilled along the lake shore and the measurements of filtration velocity and flow direction are being performed twice yearly during high and low ground water levels. To verify results obtained so far from filtration velocity measurements, a test consisting of the injection of tritiated water and the observation of tritium concentration in three rows of boreholes situated downstream was conducted. The filtration velocity calculated from the transit time of the tritiated water to the first row of boreholes was in good agreement with conventional estimates and both gave an order of magnitude of the underground inflow into the lake in comparison with classical data. It should, however, be stressed that the agreement is rather accidental and of doubtful value as in many boreholes vertical currents exist. Field observations confirmed by model studies showed that the measured filtration velocities were influenced by the vertical currents.

The geological situation in the region under consideration is very complicated in that there are many sandy, silty and loamy layers so that permeable layers are separated by many known, and also probably many unknown impermeable layers. Because of the great variability of the geological profile it may be presumed that there are many dead water zones and that the movement of water takes place only in some thin layers of unknown dimensions. Such assumptions were confirmed by tritium experiments.
which will be described below in more detail. About 50 days after the injection of tritium in May last year, the peaks of the activity were found in the first row of the observation wells. The velocity which was discussed above had been calculated from these results. Then, in October, there was a small flood which caused an increase of two orders of magnitude in the tritium content in the injection borehole. During that period some of the observation wells were under water and the ground water table was much higher than usual. In the spring there was again an unexpected flood which covered almost the whole area under investigation. Since this year has been particularly wet the area is still flooded. Surface water connected almost all boreholes and the tritium content is everywhere nearly uniform and much higher than in the peaks which were found in the boreholes of first row. That means that only a small part of the injected tracer reached the observation wells and that the velocity calculated from the transit time does not represent the average velocity of ground water flow but only the velocity of water in the thin more permeable layers. The change in the water table causes considerable changes in the flow conditions (e.g. the increase of the activity in the injection well seems to show it).

This whole experiment, unfortunately disturbed by the floods, showed that under conditions of inadequate knowledge of complicated geology it is very difficult to estimate the underground water flow rate.

It seems to be worth discussing whether or not it is possible to measure the flow rate in highly inhomogeneous water bearing strata by the injection of the tracer in one borehole and observations in some others and, if it is possible, how to do it. The questions of importance are: how to perform the injection if vertical currents exist in the borehole(s); how to observe the movement of a tracer; and under what conditions the velocities obtained really represent the underground flow.

The pumping operation, particularly that of Moosbrunn I, was tested by many methods. The measurements of filtration velocity and direction in the nets of boreholes surrounding the two pumping stations were also performed. It was possible to draw useful conclusions from these measurements of the pumping stations of RAMNEY's system in the Vienna Basin.

It appeared, however, that in this region also vertical currents existed in boreholes penetrating a relatively homogeneous aquifer, and that the measurements of filtration velocity and direction were highly influenced by them. The vertical currents were measured by MOSER's method consisting of measuring the transit time of the injected radioisotope. The measurements were performed by means of four GM probes and a special injection syringe. It turned out that inserting the measuring device in the borehole disturbed its "natural" conditions and correct results could be obtained after a pause of 20 up to 30 minutes. After this pause the "natural" conditions were re-established. We found that unambiguous results were obtained only if the vertical velocities exceeded some metres per hour. For smaller velocities another method has to be applied.

It is very interesting that such high vertical velocities were found in boreholes within a relatively homogeneous aquifer. In some boreholes the water flowed up, in some down. There were also boreholes where flow in both directions was obtained. The distances between boreholes were not larger than ten metres. This means that differences in head sufficient
to cause measurable differences in vertical flow were set up by flow of the ground water through only ten metres of partially separated soil lenses having different permeabilities.

5.1.1.3. Influence of the vertical flow in a borehole on filtration velocity measurements.

To investigate the influence of vertical flows in boreholes on filtration velocity measurements a special model was constructed. In this model it was possible to produce different gradients for the vertical flow velocity and thus vertical flows with different velocities. The model was filled with fine sand while two materials, coarse and fine-grained gravels, were used for gravel pack. The vertical current could also be observed visually with the aid of a dye through the transparent front wall of the two-dimensional model.

The measurements showed, as was expected, that the dilution of the radioisotope in the measuring part of the probe depended on the sum of the two flow rates, horizontal and vertical. The measurements were performed by means of the probe which had two rubber seals cutting off the measuring part of the borehole. It means that the vertical current flowed round the seals through the gravel pack into the measuring part of the probe. Thus the assumptions concerning the influence of vertical currents which were given in our previous paper as well as in that by GUIZERIX appeared to have been incorrect. As the dilution rate is proportional to the sum of two flow rates, the influence of vertical flow can be expressed by the factor

\[
\frac{Q_h + Q_v}{Q_h} = \frac{V_f S_y + V_v S_h}{V_f S_y}
\]

where "Q_h" is the horizontal flow rate, "Q_v" the vertical flow rate, "V_f" the filtration velocity, "V_v" the velocity of vertical current, "S_h" the area of the horizontal cross-section of the borehole, and "S_y" the area of the vertical cross-section of the measuring part of a probe.

For our probe "S_y" = "10 S_h" and it means that if "V_v" = "10 V_f", the dilution is equally caused by "Q_h" and "Q_v". In other words, if "V_v" = "V_f", the influence of vertical current on the filtration velocity measurements can be neglected. However, the measurements in the regions of Moosbrunn and Neusiedler See showed that usually "V_v" >> "V_f", i.e. the measurements of filtration velocity are practically impossible in simple boreholes. One must also note that the vertical flows disturb the natural flow lines in the vicinity of the borehole.

To stop the vertical flow during the measurement, a special construction of the borehole must be made. Such a construction will be made in the borehole drilled at Mitterndorf (Vienna Basin). In this borehole, drilled to investigate the Vienna Basin, many investigations are being performed. The measurements of filtration velocity and flow direction will also be conducted. The measurements will be performed in perforated sections, each 3 metres long. Between the perforated sections of the PVC pipes there will be 9 metres of unperforated pipes. Outside of the unperforated pipes the borehole will be sealed with impermeable material. During the measure-
ment the whole perforated section will be entirely separated from the rest of the borehole. It is, however, still possible that certain vertical currents will exist if any perforated section is located in a zone where thin impermeable interbeds were overlooked during drilling.

5.1.1.4. Measurement of ground water flow velocity by means of injection and pumping in one borehole

An attempt was made to measure the ground water flow velocity by means of the method which was proposed in Israel. As at Moosbrunn, the filtration velocity measurements were difficult to perform because of the vertical currents.

A 3mCl NH$_4$$^{82}$Br solution was injected and after a pause of some hours the pumping from the injection borehole was started. About 10 m$^3$ of tagged water was used for one injection. Knowing some geometrical parameters of the experiment and measuring the concentration of the tracer in pumped water it was possible to determine the distance which the tracer had travelled in the time between the injection and the beginning of the pumping. The relation of these two numbers gave the groundwater velocity. The water from the borehole was pumped through a vessel, into which a scintillation counter of W-11 type was inserted. The monitoring equipment was borrowed from the Weizmann Institute (Israel).

The aquifer under consideration consisted of sandy and gravelly layers with some loamy interbeds. Knowing the geological profile, it was possible to assume that there were two permeable layers of different thickness and permeability. As the injection was performed twice with two different pauses, it was possible to estimate separately the average velocities in gravels and in sands. The velocities obtained were 0.034 m/h (sands) and 0.45 m/h (gravels). The average permeability coefficient estimated from these data was 0.45 cm/s, whereas the "k" value from the pumping test was equal to 0.4 cm/s. It seems that the method described, though troublesome, may sometimes be a useful tool for the determination of underground water velocity.

5.2. Centre d'Etudes Nucléaires, Grenoble, France

5.2.1. Measurement of Vertical Velocity in a Perforated Tube

The prototype of an apparatus studied enabled the measurement of a minimum vertical current of 3 mm/s. This instrument used as a micro-current meter, can be utilized for studies of leaks from dams.

A study was made of the characteristics of the perforations on vertical currents by an electrical analogue.

5.2.2. Measurement of Horizontal Filter Velocity by Point Dilution Method

In process of development is an instrument housing a neutron source, and a cadmium salt as a tracer.

5.3. Bundesanstalt für Bodenforschung and Niedersachsisches Landesamt für Bodenforschung, Hannover, Federal Republic of Germany

Data was desired on the groundwater movement in the area of Engden,
near the Dutch border, Na$^{131}$I was mixed with the water in the borehole. The detector was a collimated scintillation probe. The velocity found was less than 36 m/year corresponding to the diffusion velocity for NaI. The direction was not ascertained.

This method was not further used after the negative experience obtained from the tests. Difficulties arise on the one hand through radioactive hazards during handling, and on the other hand through unknown adsorption of the isotopes on the gravels and sands of the aquifer.

5.4. Research Center for Radiohydrodrometry, Munich, Federal Republic of Germany

Determinations of filtration velocity $v^*_f$ (i.e. the ratio of groundwater flow to cross-section area) from the gradual dilution of a radioactive tracer solution in a filter tube filled with groundwater present the following main difficulties: (a) the drill hole itself alters the flow; (b) vertical flows often occur in the drill holes; and (c) the tracer solution in the volume to be measured does not always mix homogeneously with the unlabelled water which subsequently flows in.

To study these problems laboratory tests were carried out on a model apparatus (3 x 1.5 x 1.3 m) filled with sand or gravel (permeability constant 0.4 and 3.4 cm/s; grain size 0.5 - 1.5 mm and 2 - 4 mm) through which a simulated ground water flow with filtration velocities of up to 23 m/day was passed. Filter tubes of various diameters (principal 2" and 4") and perforations were arranged in this simulated aquifer. In some cases the filter tubes were surrounded by gravel-packed filters to reproduce the conditions found in natural formations. In some experiments the apparatus contained two layers of gravel of different permeability, one above the other. A vertical cross-section model of an aquifer (devised by J. MAIRHOFER of Vienna) was adopted by building a flat flow container of Plexiglas with which sections of any desired orientation can be simulated. It is planned to use this to supplement the results obtained with the "three-dimensional" model.

Clear and reproducible $v^*_f$ curves were obtained particularly when the volume to be measured was mixed continuously, 15 times a minute, with a wire coil mixer. The density of the tracer solution in the measurement volume can also make the measurement of $v^*_f$ and thereby of the correction factor $\alpha$, inaccurate. Experiments in 2" filter tubes with 10% perforation showed that at concentrations greater than $10^{-6}$ M NH$_4$Br/l in the measurement volume the tracer solution escapes through the packing and the measured value of $\alpha$ is consequently too high.

Measurements of $\alpha$ as a function of filtration velocity in the range 0.1 - 23 m/day showed that $\alpha$ is constant as predicted theoretically so long as the flow in the filter tube is laminar.

We tried to take into account the effect of a filter tube on the ground water flow field by assigning to the wall of the tube a permeability $x$.

$v^*_f$ is the measured filtration velocity (with the correction factor $\alpha = 1$). It is obtained from the (theoretically linear) relation $\lg c/c_0$ as a function of time ($c$ = tracer concentration).
constant analogous to the aquifer and, where applicable, to the gravel filter. For filter tubes with diameters from 2" to 4", in the range of \(v_f\) and \(r\) (= perforation) investigated, we found the permeability of the tube to be approximately linearly dependent on the perforation, however, this approximate linearity can be disturbed by unfavourable geometric positioning of the slits. The usefulness of introducing filter tube permeability was apparent from the fact that measurements of \(\alpha\) gave a constant value for tube permeability within the limits of error; this was true (a) for particular tube in soils of different permeability and (b) for different tube-wall thicknesses, with constant perforation and constant soil permeability.

To calculate \(\alpha\) from laboratory tests in which 2" and 4" filter tubes were surrounded by a gravel filter of up to 30 cm diameter, the OLIVI formula was expanded and made applicable to a three-layer problem. Taking filter tube permeability into account \(\alpha\) values of about 2.1 - 3.1 were obtained.

In the flat Plexiglas flow container tracer dyes have been used to investigate flows through filter tubes with and without gravel filter, and with and without test probes inserted in the homogeneous or stratified "aquifer". From the flow patterns determined in this way the correction factor \(\alpha\) can easily be obtained. An experimental study of the relationship between filtration velocity (within the filter tube) and the actual velocity of ground water flow (outside the filter tube) has also been started.

In flow experiments on superjacent soil layers having different permeability constants (0.4 and 3.4 cm/s) one would expect from Darcy's law that the filtration rates would behave like \(k\) values. The \(v_f\) measurements gave a very precise indication of the boundary between strata. The \(\alpha\) value, calculated from filter tube data and data on the permeability of the soil layer, which are assumed to be known, served as a means of calculating the true filtration rates \(v_f\) from the measured filtration rates \(v'_f\) for each separate layer. In this way the "flows" in the separate soil layers were determined, and their sum differed by 5% at most from the known total flow.

In conclusion it is well to point out that the accuracy with which the true filtration velocity \(v_f\) can be determined in field experiments depends largely on the accuracy with which the characteristics of the filter gauge (diameter, perforation and permeability of the tube; diameter and permeability of the gravel filter) and the permeability constants of the different soil strata are known.

Vertical flows often occur in filter tubes which are perforated over a considerable length and pass through soil strata of different permeability of different water pressure. To measure these tracer solutions are injected and their downward or upward flow at a number of measuring points followed. From the average flow velocities obtained in this way and from the sum of the pulses one can calculate the size and position of influent and effluent flows in the vertical profile of the drill hole. Some aspects of this method require further study, for example the relationship between vertical flows measured in filter gauges, filtration velocities in the same region measured by \(v_f\) probes (with packing) and flow phenomena in the surrounding soil.
In the laboratory tests to determine the direction of flow (described below) the tracer ($^{131}$I, $^{82}$Br, $^{198}$Au) was measured with a collimated gamma-counting tube after its emergence from the filter tube. The experiments were performed in a flow chamber with an effective length and width of 1.2 m and a height of 0.9 m, filled with gravel of 2 - 4 mm grain size and adjusted generally for a filtration rate of 2.5 m/day. The filter tubes used were primarily 2" steel pipes with brass mesh casings. The flat Plexiglas flow container was also used to make the angle of aperture visible with tracer dyes (beneath it a directional probe installed in the filter tube "sees" the effluent tracer) and to carry out experiments aimed at reducing the angle of aperture for the tracer distribution in the soil.

Useful direction measurements are most likely to be obtained when the tracer distribution in the soil undergoes no appreciable change during the whole time required for measurement, i.e. when adsorbable tracers are used. To compare the adsorbability of different tracers in the region of the filter tube the pulse rates were measured at times when there was no longer any dissolved tracer in the tube. The tracers used were radioactive solutions of $^{131}$I, $^{123}$I, $^{103}$I and $^{198}$Au of different chemical concentrations; for the most part these were homogeneously distributed in the filter tube at the outset. The results showed that adsorption in the neighbourhood of the filter tube increases, as one would expect, when the initial concentration of the tracer is reduced, and that adsorption of $^{198}$Au is considerably stronger than of $^{131}$I. Adsorption of carrier-free iodide is strongly dependent on the filtration velocity when $v_f \approx 1.5$ m/day but only slightly dependent at larger $v_f$ values. Presumably $^{131}$I is partially oxidized in these very small concentrations. Practically no adsorption could be detected when $^{82}$Br was used in the form of $\text{NH}_4\text{Br}$, at initial concentrations in the filter tube of about $1 \times 10^{-5}$ M/l.

Adsorption of $^{131}$I in the region of the filter tube could be increased if a $\text{AgNO}_3$ solution were first allowed to flow out of the tube into the aquifer and an $^{131}$I solution subsequently injected in the tube. Simultaneous injection of both solutions in two separate superposed packings, as suggested by BROROWSKY (19), produced a similar result.

If the tracer is not injected homogeneously in the tube but at specific points and centrally, a more distinct direction diagram is obtained which allows a more precise determination of the direction of flow.

In connection with a projected underground railway system for the city of Munich, filtration velocities have been measured in 34 filter gauges (at about 5 - 12 m depth of water). A certain amount of information on ground water flow in the Munich area has been obtained in this way.

At a well system in north Munich "k" values obtained by pump experiments were compared with corresponding values obtained by the point dilution method. The agreement was generally good: in one of the two wells the results were identical whereas in the other there were discrepancies of 30 %.

Later chromatographic tests on the $^{123}$I and $^{103}$I solutions (prepared in the usual manner from $^{131}$I) showed that the oxidation did not follow a quantitative pattern.

A suggestion of J. MAHRHOFER, Vienna
Other comparative measurements were carried out at a small power plant on the upper Isar where underground flow conditions were comparatively familiar from earlier measurements. It was desired to know what relationship exists between the vertical flow in the filter gauges and the filtration velocities measured in packer probes by the point dilution method. Although many problems remain unsolved, it was apparent from the first experiments of this type that the old method of determining water exchange between a drill hole and the surrounding subsoil from changes in vertical flow gives values which are compatible with filtration velocities obtained from dilution measurements.

In another field experiment in Lower Bavaria measurements of filtration velocity and flow direction are being made to see whether the ground water of a valley meadow is affected by seepage from the slopes and by a nearby stream.

Observations of seepage under the dam of the Sylvenstein reservoir - a long-term project - were continued this year. A first summary of the results of these observations was presented at the 1965 Congress of the International Association of Hydrologists in Hannover.

5.5. Institute of Nuclear Research, Cracow, and Geological Institute, Warsaw, Poland

Application of radioisotopes in hydrology was started in Poland three years ago. It has been seen that "point methods" are useful for the determination of underground flow characteristics and of aquifer parameters and that these methods, though limited, might be a useful tool in an early stage of the investigation of the aquifer. The point dilution method, flow direction measurements by the single well technique, and measurements by means of the universal probe are understood here as the "point methods". Because of their simplicity it may be hoped that they will find wide application in practice.

5.5.1. Measurements of Flow Direction and Velocity

The point dilution method of filtration velocity measurement and the single well technique of flow direction determination, though very simple in principle, are not very easy to apply in various conditions. The technique of field measurements applied in Poland will be described before more general discussion of the limitations of the methods.

For velocity measurements probes with GM counters without any seals and special mixing devices are used. The tracer is injected and mixed along the whole borehole or, in some cases, only in the perforated part. Several measurements performed in six different regions gave very good results in comparison with those obtained by classical methods (some results were published 20, 21) whenever measurements were performed in boreholes having a small diameter (2 - 3 inches) or if, for diameters larger than 3 " and for boreholes in fine soils, the tracer was gently mixed by moving the probes along the axis of the borehole. In boreholes with larger diameters the results obtained without mixing were 4 - 8 times higher than expected. This means that in good agreement with results obtained by

This work was developed in Poland in close cooperation with Dr. J. MAIRHOFER of the Bundesversuchs- und Forschungsanstalt, Arsenal, Vienna.
GUZERIX et al. (16) and BOROWCZYN et al. (15), it is possible to measure the filtration velocity without mixing only in the boreholes having a small diameter. The technique for velocity determination was used in boreholes with depths up to 80 metres, whereas the direction measurements by means of the technique described by BOROWCZYN et al. (19) were performed at depths up to 35 metres. Both kinds of measurements were performed with \( ^3 \)H which appeared to be very good for direction measurements in gravelly and sandy layers, whereas for velocity measurements a high final background was obtained.

As various techniques are applied by many investigators it seems advisable to consider their advantages and limitations. In Table IV are given the permeability coefficients, filtration velocities and measuring times for the different categories of rocks and soils. The filtration velocities are given for different heads whereas the times are calculated for the 2" boreholes and for two decreasing concentrations of the tracer. The measuring time for the decreasing of the tracer equal to 0.1 (expressed in units of initial concentration \( ^{\circ}C \)) seems to be a minimum if the construction of a probe or the kind of tracer did not allow the neglect of the final background. The time for \( C_0 = 0.01 \) gives the approximate value of minimum pause between the injection of isotope and the direction measurement. For boreholes with larger diameters than 2" the measuring times will be proportionally longer than those given in Table IV. It follows from Table IV that there are soils and hydraulic gradients for which the point dilution method seems to be useless.

In Fig. 3 the ranges of velocities which are covered by the different kinds of probes are given. Common probes, owing to the lack of seals can be moved along the axis of the borehole during the measurement. In this way the changes in the concentration of the tracer at different depths can be observed, and the profile of filtration velocities will be obtained in a reasonable time. Although the range of velocities covered by the probe(s) without seals is smaller than for the probes with seals it comprises the conditions which are usually met in nature.

5.6. Discussion

The discussion brought up again the limitation of vertical currents on the measurement of horizontal filtration velocities. It was pointed out that these currents are frequent in nature. They are caused, for instance, by differences in permeabilities of two or more layers, partly separated by an impermeable one. It is necessary to analyse the significance of the vertical flow for the immediate hydrological problem and to develop methods to eliminate them when it is necessary to accurately measure the horizontal filter velocity.

Some disturbances are caused by drilling. Replacing the original sequence of soil materials around the well casing to minimize such effects cannot be recommended for general practice because of high cost and possible adverse effects on the productivity of the well.

Attention was called to the use of different terms (\( \xi \), \( \xi \) and \( \xi \)) for the same parameter and the need for unification, perhaps through the use of a dimensionless parameter. Some discussion followed on the dependence of these factors on the shape of perforations.
The single-well method developed in Israel was mentioned by several participants arguing that the method gives a better representation of the aquifer. It was noted that information on the details of the method are not generally known. Further comparison between this and the point dilution method were strongly suggested.

Future research, especially in Austria and in the Federal Republic of Germany, will be directed forward to determine the actual limits of the borehole methods, devising the best borehole form and construction methods and will investigate the reasons for vertical currents.

6. GROUND WATER TRACERS

6.1. Centre d'Etudes Nucléaires, Grenoble, France

6.1.1. Use of $^{51}$Cr-EDTA

The kinetics of fixation, and thus an integration of $^{51}$Cr-EDTA on activated charcoal was studied. As a result of the study only 10 $\mu$Ci of $^{51}$Cr are needed to mark 10 m$^3$ of water.

6.1.2. Utilization of non-active "NaI"

In this method non-active iodine is measured by an isotopic exchange with $^{131}$I. The method was introduced at C.E.N by RICHTER ($^{51}$Cr).

It is of interest in problems of small scale ground water hydrology and in measurements of river discharge. The minimum measurable concentration is about 0.001 ppm. The first exploitation is taking place at Mont Conis.

6.2. The Weizmann Institute of Science and Water Planning for Israel, Israel

A series of experiments were performed in which several tracers were compared. In a laboratory study $^{24}$Sc-EDTA, $^{51}$Cr-EDTA, $^{56}$Co(CN)$_6^-$ and tritium were compared in columns of sand, dolomite and basalt. In two field experiments, comparisons were performed between chlorides, $^{56}$Co(CN)$_6^-$ and pentacyl pink B. In dolomites there was always an adsorption of the dye with respect to the other two tracers which were quite comparable. Results will be published shortly.

6.3. Chalmers University of Technology, Goteborg, Sweden

6.3.1. Laboratory Evaluation of Gamma-Emitting Tracers for Ground Water with Special Regard to $^{51}$Cr-EDTA

The purpose of the investigation is to carry out a series of careful laboratory tests on the suitability of some gamma-emitting nuclides as ground water tracers. Mainly, the intention is to determine the lowest concentration at which $^{51}$Cr-EDTA is not retarded or adsorbed in various mineralogical environments, under different conditions of "pH" and in soils of various clay content. If $^{51}$Cr-EDTA does not possess the properties required other gamma-emitting tracers will be tested. "HTO" is used together with the gamma-emitting tracers as a reference.
The measurements of $^{51}\text{Cr}$ are made by means of a well-type scintillation counter, at the Isotope Techniques Laboratory, Stockholm. The measurements of $^2\text{H}$ are made with a two-channel liquid scintillation counter (Packard Tri-Carb) donated by the IAEA. Simultaneous counting of $^{51}\text{Cr}$ and $^2\text{H}$ has been achieved using pulse height analysis. If the $^{51}\text{Cr}$-activity of the samples is not very low, the simultaneous counting is useful. Concerning the $^2\text{H}$-measurements it is possible to discriminate and correct for $^{51}\text{Cr}$-activity and therefore it is not necessary to wait with the $^2\text{H}$-measurements until the $^{51}\text{Cr}$-activity has decayed. The use of flow cell or flow detector for continuous measuring during column tests had been studied. It seems to be a very convenient method in some types of investigations.

About one hundred column tests have hitherto been executed. The preliminary results of the tests in various mineralogical environments are shown in Table V. $^{51}\text{Cr-EDTA}$ at the concentration of 0.001 ppm is neither adsorbed nor retarded or very slightly retarded in quartz sand, quartz sand mixed respectively with 10 % quartz powder, calcite powder, microcline powder and muscovite powder. There is some adsorption and very slight or slight delay of $^{51}\text{Cr-EDTA}$ at the concentration of 0.01 ppm in quartz sand mixed with 10 % of either albite powder, anorthosite powder, and biotite powder. Concerning hornblendes and augites there is a considerable delay of $^{51}\text{Cr-EDTA}$ at the concentration of 0.01 ppm in both of them but a considerable adsorption only in augite.

Among clay minerals, chlorite gives rise to a very long delay of $^{51}\text{Cr-EDTA}$ at the concentration of 0.01 ppm, bentonite (montmorillonite) to a long delay and strong adsorption of $^\text{HTO}$, illite shale to a long delay and strong adsorption of $^{51}\text{Cr-EDTA}$ and to a long delay of $^\text{HTO}$, and kaolinite to a certain delay of $^\text{HTO}$.

Some tests have been carried out in soils of different kind. In a tight fine-sandy till soil there is a considerable delay and adsorption of $^{51}\text{Cr-EDTA}$, but not in sandy and gravelly soils. Ground water within the $^\text{pH}$-range of 5.8 to 8.5 is used. The capacity of the pump has been changed to get different flow rate in the column test. $^{51}\text{Cr-EDTA}$ is not influenced either by changes of $^\text{pH}$ or by changes of flow rate.

To summarize, $^{51}\text{Cr-EDTA}$ is shown to be a completely reliable tracer down to 0.001 - 0.01 ppm in silt size, sand size and gravelly mixtures with a mineralogical composition of common minerals. Naturally it is also reliable in fractured rocks consisting of the minerals mentioned here. In soils and fractured rocks containing clay minerals there is a delay and adsorption, $^\text{HTO}$ is also delayed and adsorbed in montmorillonite and delayed in illite and kaolinite.

The laboratory tests will continue in order to complete the tracer test series. In the field two large-scale tests are planned to be carried out together with the Water Protection Service of the National Road Board in Sweden.

6.4. Discussion

The discussion centered around three main points: The interpretation of KNUTSSON's working paper, the character of tritium adsorption in
minerals and the meaning of the term "ideal tracer".

6.4.1. $^{51}\text{Cr-EDTA}$

All minerals in which there is a delay of $^{51}\text{Cr-EDTA}$ are basic minerals. These are characterized by the presence of iron, manganese, magnesium and calcium. In the presence of these metals in certain "pH" ranges there will be an exchange for chromium and a precipitation of the latter. The minerals which show "HTO" retardation are the expanding clay minerals.

6.4.2. Tritium

Some investigators (recently STEWART of USGS) have shown that tritium is adsorbed. LEVYQUE thinks it is a non-reversible adsorption that changes some of the characteristics of the minerals. Other participants thought that the delay of tritium is a reversible phenomenon and represents an exchange with adsorbed water. The exchange with structural water may be irreversible under some conditions.

The delay of "HTO" is significant for water studies. Two cases have to be distinguished here. If bulk phenomena are studied then the retardation of "HTO" should be considered as an adverse phenomena and "HTO" can no longer be considered an ideal tracer for such studies. On the other hand, if the movement of a particular slug of water is studied, then the behaviour of "HTO" is the true representation of the marked body. The last statement is valid if the delay of "HTO" is not caused by an irreversible process.

6.4.3. Safety Aspects

A note in publication (23) stressed the point that it is not always the short-lived isotope that is the safest. The relatively high initial concentrations of short-lived isotopes constitutes a greater hazard in the initial steps of some experiments.

The IAEA is preparing a manual on the subject of the safe use of radioisotopes in hydrology.

6.4.4. Activation Analysis

Although the idea of activation analysis of stable nuclides was discarded in the past for the purpose of ground water tracing, constant awareness to developments of new neutron generators should be kept in mind considering that they may create new possibilities.

7. MEASUREMENTS OF AQUIFER PARAMETERS IN THE SATURATED AND UNSATURATED ZONES

7.1. Centre d'Etudes Nucléaires, Grenoble, France

For the last 18 months a special effort has been made to encourage the utilization of the neutron probe. A method for the calculation of the thermal flux was established. Currently, a simultaneous measurement is made of the moisture content and the density of a soil by a single apparatus.
Throughout the last year, tests concerning the reliability of the gamma-lysimeter in the field as well as on the possibilities of its use were carried out. Technical defects did not occur. Due to its strong stratigraphical resolving power of 6 cm and the exactness in measuring a density variation of \( \pm 0.002 \) g/cm\(^2\), it was possible to determine the wet-density, and from this, to calculate the ground water storage capacity. There are no difficulties in observing the movement of the maximum of humidity in vertical direction. For instance, a velocity of the maximum of humidity of 2.7 cm/h was found. But this apparatus cannot record the absolute flow rate of water.

The operation of the gamma lysimeter is shown in Fig. 4. A 20 mCi-\( ^{137} \text{Cs} \)-source is gradually lowered into a vertical hole parallel to a scintillation detector which is lowered into a parallel hole at a distance of about 50 cm. Since the source has a collimator a greater stratigraphical resolving power is obtained. Measurements are made for 5 minutes with source and detector at the same depth; readings are taken every 6 cm. A few typical density curves obtained after rainfall are given in Fig. 5. From these curves it is seen that with increasing depth a shift in the wet-density maximum along the time axis takes place. It may be mentioned here that the velocity of the wet-density maximum is higher than the actual seepage velocity which, according to the methods of ZIMMERMANN, MÜLLNER et al. (24) can be measured by means of deuterium injections.

Investigations dealing with errors in determining the density by gamma-lysimeters were carried out by LORCH. When inserting a casing into a soil a change of the original density of soil within the neighbourhood of the disturbance takes place. It is not known whether such systematic examinations concerning this problem have previously been carried out. LORCH built a model box having a cross section of 1 m\(^2\) and a thickness of 10 cm. This box was filled with dry and wet sands of different grain-sizes. Wooden disks were pushed in. By using a gamma-detector, measurements of the density variation depending on the distance from the disturbance were carried out. In all cases one observed that the soil became only slightly compressed in the neighbourhood of the disturbance. This change in the density reaches a maximum and it gradually decreases to its natural value with distance from the centre of the disturbance. By using a 1 cm thick detector disk in a sandy material of a density of 1.5 g/cm\(^3\) a disturbance area with a diameter of 15 cm was caused. The corresponding values for detector thicknesses of 2 cm and 6 cm were found to be 25 cm and 45 cm, respectively. The tests will be continued by using clay material.

The following is a summary of a paper presented at the IAEA Symposium on Radioisotope Instruments in Industry and Geophysics, Warsaw, October 1965. The reader is referred to the original publication for full details (25).
7.3.1. The Problem

Our research center is engaged in the development and testing of tracer methods to investigate ground and surface water flows. The reliable interpretation of tracer measurements of ground water flows calls for a faultless (and known) borehole development (that is a filter gauge surrounded by a gravel filter). In addition, the knowledge of the density and total water content or the pore volume of the soil is of interest. As a supplement to the tracer measurement of ground water flows, we therefore will perform measurements of the density and moisture content according to the $\rho \mu^>|$- and $\mu$-methods. These measurements frequently have to be made on 2-inch filter gauges already existing which are surrounded by a gravel filter and may reach down to depths below 100 m. The gravel filter increases the distance between the logging tool in the gauge tube and the soil whose density and moisture are to be measured (Fig. 6). For this reason we have conducted some preliminary tests in the laboratory to determine what influence the gravel filter and the dimensions of the gauge tube have on the measurements.

7.3.2. Density Measurements by the $\rho \mu^>|$-Method

For the density measurements we used two different scintillation counter-probes with an outside diameter each of 4.5 cm. Probe "A" contained 5 mc $^{137}\text{Cs}$ at a distance from the detector crystal of 20 cm. Probe "B" contained 10 mc $^{\text{RA}}$, the separation source - detector crystal being 55 cm, 60 and 100 cm, respectively, as diameters for the measuring containers proved sufficient, that is as quasi-infinite. To imitate the filter gauge, a solid-wall iron pipe, closed at the bottom was placed in the center of the respective measuring container. A thin-walled tube of aluminum or plastic and likewise closed at the bottom, served to separate the gravel filter from the soil.

Different sands, fine and coarse gravels were used as soil materials, their densities ranging from 1.2 to 2.5 g/cm$^3$, depending on the moisture content. Corresponding to the conditions in a real ground water duct, the measurements mostly were performed with water-filled tubes and water-saturated gravel filters.

7.3.3. Results

To lower the influence of the gravel filter we initially tried to separate the single-scattered gamma quanta in the soil from the gamma quanta scattered in the gravel filter by energy discrimination. Owing to the scattered radiation arising in the scintillation crystal, and the multiple scattering occurring in the soil, this test did not produce the desired results. As expected, measurements without gravel filter revealed that the intensity of the scattered radiation and thus the counting rate decreases sharply as the wall thickness of the iron gauge tubes grows. For a constant wall thickness of the gauge tube the counting rate depended only lightly on the tube diameter when it was varied between 5 and 10 cm.

The laboratory measurements on gauge tubes with gravel filter were made without pulse-height analysis. It was ascertained empirically that the logarithm of the counting rate is proportional to the logarithm of the diameter of the boring. The slope of this straight line (assuming a con-
stant density of the gravel filter) is a function solely of the density $P_a$ of the soil and not of the dimensions of the gauge tube. Fig. 7, left, shows the dependence of the counting rate normalized to water on the boring diameter for different soil densities $P_a$. The extrapolation of this family of curves results in a common intersection "S", the abscissa of this point may be regarded as approximate diameter of the effective measuring volume of the density probes. Density calibration curves for any borehole diameter can be readily obtained from the diagrams on the left side of Fig. 7. As the boring diameter grows, that is with increasing diameter of the gravel filter, the calibration curves flatten off. It can be noted that the calibration curves of Probe "B" are steeper than those of Probe "A", which permits a more accurate density reading. We also examined the dependence of the counting rate on the density of the gravel filter, all other parameters remaining constant. These supplementary measurements can be used to construct, from Fig. 7, calibration curves for any values of gravel filter density and tube diameter.

7.3.4. Testing the density probe in the field

First field measurements on a storage dam allowed a precise localization of a drainage duct which had a disturbing influence on tracer measurements of seepage flows. On occasion of other field measurements, the count rate log obtained with Probe "A" showed such high rates at some depths that no density values could be assigned to them from the density calibration curves. The filter gauge probably was not developed properly so that some water-filled cavities had formed. These tests revealed that it is advisable, due to the different measuring volumes covered, to use both density probes in running a log.

7.3.5. Testing moisture measurements according to the nn-method in the laboratory

For the moisture measurements we had at disposal a logging instrument which incorporates a LiI-crystal detector separated by lead from a 10-mc Ra-Be neutron source, the distance between detector and source being 10 cm. By gradually increasing the container diameter, the size of the quasi-infinite measuring volume as a function of the moisture content was determined. To be able to vary the moisture in the gravel filter and in the surrounding soil independently of each other, the borehole wall was simulated by a thin-walled aluminum tube, which practically does not influence the moisture measurement. Quartz sand and medium-grain gravel served as soil material and filter gravel respectively.

Defined moisture contents between 0 and 100 % in any desired graduation were produced for the calibration measurements. This was accomplished by mixing quartz sand with a stiff gel, which can be made from water and gel-forming amorphous silicon dioxide in a proportion by weight of 10 : 1.

7.3.6. Results

In agreement with the theory, the measurements of calibration curves disclosed a maximum of the counting rate for growing separation
source-detector which becomes displaced toward lower moisture values (Fig. 8). The dependence of this calibration curve pattern on the source-detector separation can be easily interpreted by comparing the distance of the detector from the neutron source with that distance at which the neutrons become thermic. Further measurements carried out with the given logging tool served to study the influence of the tube filling (air or water), of the tube diameter and of the tube wall thickness.

The next and last figure (9) contains moisture calibration curves for various thicknesses of the gravel filter at a constant moisture of the (water-saturated) gravel filter. It can be seen that the given probe is not suitable for the measurement of moisture above 35% in water-filled 2-inch tubes. Apart from this, our investigations so far on moisture measurements showed that a systematic recording of the influence of the various parameters as with the density measurements is difficult. It will be indispensable before each field assignment to calibrate the neutron probe in a laboratory setup that simulates the field conditions as closely as possible.

On the whole, the test proved that the measurement of both density and moisture from a 2-inch filter tube can be noticeably influenced by gravel filters with a diameter greater than 20 cm.

7.4. Geological Institute, Warsaw, Poland

A special device, a so-called universal probe, has been developed for civil engineering purposes (25, 26). The probe, however, seems to be a very useful tool for water bearing strata down to a depth of 20 metres. The probe enables the measurement of specific resistivity, bulk density, volume moisture and eventually compaction of the soil. Knowing these parameters the determination of the lithology and the porosity of the soil is possible. A special vibration hammer facilitates the driving of the probe in or out of the soil very quickly, so that many observation points can be obtained in a reasonable time and at a reasonable cost.

By means of the vibration hammer it is also possible to drive in the thin pipes for measurements of ground water velocity by transit time method. Such measurements may be performed in natural conditions or during the pumping test. Knowing the hydraulic gradient and porosity it is possible to calculate the permeability coefficient of particular strata since the injection can be done at any depth, because the injection pipe is perforated only in the lower part. Additional equipment makes it possible to obtain water or soil samples. Driving a perforated tube in the soil it is also possible to conduct the filtration velocity and direction measurements by isotope or electrical methods. The whole equipment will soon be commercially available.

7.5. US Bureau of Reclamation, Denver, Col, USA

Neutron scattering is being employed to study the soil moisture as part of a broad programme to investigate the use of water on Federal irrigation projects. The purpose of the basic programme is to investigate the amount of water used in irrigation to determine the present and attainable irrigation efficiency on the basis of initial and final soil moisture,
computed consumptive use, and amount of water applied. In the Weslaco, Texas area, because of limitations in estimating consumptive use, a detailed measurement of soil moisture is used to evaluate consumptive use. Approximately two dozen sample tubes have been installed for neutron measurements of soil moisture. Although some instrumental difficulties have been experienced, tests are still in progress but no preliminary results are available. Of particular interest to the programme would be other studies concerning the reliability of neutron scattering in the measurement of soil moisture in agricultural soils and quantitative data on the effects of salinity.

7.6. Discussion on n-n and v–γ methods

Further reports on availability of instruments and utilization were given by Denmark (The "Mastodon Appendix" developed by Isotopcentralon for n-n measurements in the saturated zone. Experience on coastal bottom materials); France (Experience in Algeria and study of the capillary zone. Measurements of the unsaturated zone changes were pertinent to flood predictions in sensitive areas); Israel (A convenient neutron source from the reaction of α on 18O in the form of C18O2. The source does not have to be shielded and there is no activation of the crystal).

The discussion pointed to the following pertinent points:

a) In most cases both n-n and γ–γ methods are necessary to obtain complete information.

b) Optimum source to detector distances are different for the two methods and thus an optimum single probe housing both n-n and γ–γ devices is hard to construct.

c) The resolution of a probe depends on the size of the detector. In cases which require fine resolution a narrow detector, or a collimated one, should be used.

d) Opinions were expressed concerning the reduction of the sphere of influence.

e) Most of the uncertainties in commercial instruments are in the measurement of moisture contents approaching saturation.

7.7. Parameters Other Than Moisture Content and Density of the Saturated and Unsaturated Zone

7.7.1. Geological Survey, Denmark

The following is an abbreviated version of a paper by Andersen presented at the IAH Congress, Hannover, 1965.

"The Variation of Tritium Concentration with Depth in the Upper Part of an Unconfined Ground Water Aquifer in South Jutland, Denmark."

The ground water samples were taken during the drilling of a well for the waterworks of Hjordkær, 7 km S.W. of Aabenraa, Denmark. The position of the well is shown in Fig. 10, where contours of the ground water table, the depth to the ground water table and observation wells
are shown. The discharge from this well can be estimated at about 50,000 m³/year.

The aquifer in this area consists of unconsolidated gravel, sand and silt deposited as outwash from the last glaciation (Würm), on the heath plain of Tinglev. The western limits of the last glaciation, "the main stationary line", roughly coincides with the ground water divide as shown in Fig. 10. The ground water table around the investigated well is about 2 to 4 m below ground level, with increasing depth to the east.

Fig. 11 shows the log of the well, the levels in which the water samples are taken, and the concentrations of tritium in samples No. 1, 6, 8, 12 and 13.

The water samples No. 1 - 12 were taken during the drilling of the well. Sample No. 13 was taken in a nearby pumping well 10 m E of the well.

The well was drilled by the cable tool method. Above the water table the material was removed by a handoperated earth auger, and below the water table by a bailer. No water had been added to the hole during the drilling. The diameter of the casing was 12 in, and the casing was kept near the bottom of the hole to avoid caving. The water table was 3.4 m below ground level. Above the water table two samples of silty clay were taken and the soil moisture was evaporated by distillation.

Below the water table an amount of water, corresponding to the volume of the hole below the water table, was removed from the hole by the bailer before sampling.

The results of the analyses are shown in Fig. 16. The analyses were made in April 1965.

It will be seen, that the tritium activity is highest in the suspended water just above the water table, 647 T.U., and decreases very fast a few metres below it. The ground water 3.3 m below the water table contains only 85 T.U. and the pumped water from about 16 - 22 m below the water table has a tritium content of 4.81 T.U.

Interpretation of this data requires a knowledge of the amount of the seepage water and of the tritium concentration of this water.

Measurements of tritium in precipitation from Denmark are only available from short periods. Therefore correlations will be made with the data from Huddinge, Stockholm. After ODEN (1964) (24), the tritium concentrations of the precipitation from Jutland should form 80% of the values of Huddinge. The data from Huddinge 1958 - 1962, which have been published in Tellus vol. XVI p. 124, and the data from 1963 - 1964, which originate from a personal communication from NILSSON, Geological Survey of Sweden, are shown graphically in Fig. 12. Further the amount of the
precipitate in South Jutland (in average of several stations), the estimation of actual evapotranspiration are shown, and finally a graph showing the fluctuations of the ground water table in a well DGU file No. 159.29 in the same aquifer but about 12 km to the west of the above mentioned well.

Part of the rain falling on land infiltrates the upper part of the soil, and moves slowly downward towards the ground water. A considerable amount of this soil moisture will never reach the ground water, because evapotranspiration by plants returns it again to the atmosphere.

Estimates of the monthly amount of the actual evapotranspiration are:

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain</td>
<td>0</td>
<td>5</td>
<td>16</td>
<td>38</td>
<td>53</td>
<td>61</td>
<td>70</td>
<td>60</td>
<td>47</td>
<td>30</td>
<td>1.5</td>
<td>5</td>
</tr>
</tbody>
</table>

Major ground water recharge will only take place during the months when the precipitation is larger than the evapotranspiration. This is seen in Fig. 17 by correlating the graph of the ground water table fluctuation and that of precipitation and evapotranspiration. The difference between the precipitation and the evapotranspiration will determine the amount of recharge water, and the tritium contents in this difference will determine the tritium activity of the ground water.

Therefore, the great peaks of tritium in the summers of 1962, 1963 and 1964, will not appear in the same concentrations in the seepage water and the ground water because the evapotranspiration exceeded the precipitation in several of these months.

If the field capacity of the soil layer above the ground water table and the porosity or the water content below it, are known, it will be possible to compute the amount of stored water above a given depth, and with knowledge of the tritium concentration of the seepage water, it should be possible to estimate the concentration of tritium at a given level.

Such a correlation between the measured and the computed tritium contents of the water can only be done from the two upper water samples, 3.2 m and 6.7 m below ground level, because the tritium concentration of the precipitation is not available prior to March 1958. Assuming a field capacity above the water table of about 10% and a porosity of the aquifer below it of about 33%, the volume of the stored water down to about 8 m below the ground level corresponds to the volume of seepage water during the period 1958 - 1964.

The tritium activity of the soil water at 3.2 m below ground level has been computed to 360 - 1,200 T.U. The measured value is 647 ± 35 T.U. The corresponding values at 6.7 m below ground level are 50 T.U. and 85 ±67 T.U. respectively.

There is no discrepancy in the measured values and the computed ones, but a significant correlation will require a larger series of observations.
If the correlation is correct the age of the soil water at the
two depths should be 1 1/2 and 3 years respectively.

The latter age determination may be made with a certain reserv-
ation on account of a possible mixing of the ground water by the
percolation. The pumping effect from the nearby water supply well will
increase the mixing of the ground water at different levels.

The low tritium concentration of the water from sample No. 13,
20 - 25 m below ground level in the water supply well (file No. 160.55),
4.81 ± 1 T.U. shows either an age of the ground water of 10 - 15 years
or a mixing of older and younger ground water. In the latter case, the
relative amount of younger water has to be low.

7.7.2. Physics institute, University of Heidelberg, Federal Republic of
Germany

The following is a summary of a paper by ZIMMERMANN and
MUNNICH et al., presented at the International 14C and 3H Dating Conference,

"Downward Movement of Soil Moisture Traced by Means of Hydrogen
Isotopes. Evaluation of Evapotranspiration."

In substance the rainwater traverses the unsaturated soil layers
above the water table very slowly. The velocity may be below one meter
per year, if the moisture content (field capacity) of the soil is high.
A single "rainfall" artificially spiked with isotope tracer will form
a marked layer of water, which, although blurred by diffusion effects,
moves downward as a distinguishable boundary between the older rainwater
below and the younger rainwater above. For any period of time that is not
too short one can therefore draw up a balance between incoming rain,
evaporation loss and the water present in the soil which eventually
reaches the ground water. The advantage of the method is that it provides
detailed information on the water balance without disturbing the natural
conditions, as well as being applicable everywhere at low cost.

Fig. 13 presents the model under consideration. Essentially, the
downward movement of the soil water depends merely on the field capacity
of the soil. This field capacity "f" ranges between 10 % by volume for
course and 40 % by volume for fine grained soil. If evapotranspiration
is negligible, the rain simply saturates the soil to field capacity to
a certain depth, pushing the old water ahead of it. We have the relation

\[ R = s_{max} \cdot f \]  

(1)

(R = rain depth in cm, \( s_{max} \) = corresponding maximum possible advance in cm)

\[ \text{(1)} \]

In view of the fact that "f" may not be constant over the whole depth
of the profile due to varying grain size and that the actual moisture
content "F" (Vol. %) may well be smaller or even larger (E.g., shortly
after a rainfall) we shall in the following replace "f" by "F", the
average moisture content between the tracer maximum and the soil surface.
Equations (1) and (2) remain valid nevertheless.
which is actually a material balance. If part of the rainwater vanishes due to evapotranspiration, eq. (1) changes to

\[ R^e = s \cdot f \]  
(2)

\( R^e = \) rain depth minus evaporation loss = ground water recharge, \( s = \) actual displacement of the boundary between old and new water.

In reality, of course, the boundary does not remain exact, but is blurred by several diffusion-like processes.

An example of actual movement of tritium tagged water is presented in the sequence of moisture and tritium profiles of Fig. 14. Here "F", the heavy line represents the soil moisture in volume percentage, and "q" (boundary of the hatched area) is the amount of tracer per 10 cm layer of soil, as a percentage of the amount of tracer originally applied to the soil. Profiles (a) to (e) represent the situation after 4, 26, 82, 152 and 214 days after tracer application.

For the period between tracer input and the date of sampling one obtains from eq. (1) and (2) the relative evapotranspiration

\[ \delta = \frac{R - R^e}{R} = \frac{R - s \cdot F}{R} = \frac{s_{\text{max}} - s}{s_{\text{max}}} \]  
(3)

The quantity "s" is the displacement of the boundary (marked by the tracer) between old and new rainwater, it is equal to the distance between the maximum of the tracer concentration measured and the soil surface, as can easily be seen from the model outlined in Fig. 18.

We shall now discuss briefly the effect of the possible presence of holes due to the activity of earth worms and other animals or of cracks in a dry, heavy soil. To what extent such holes act as pipelines for the water obviously depends largely on the intensity of rainfall and the plant cover. Heavy rainfall and low interception by plants may cause a considerable by-pass of water running through larger holes and cracks with a velocity which does not allow for substantial exchange with the soil moisture. Should this be the case, this water can overtake the tracer mark if the cracks and holes penetrate the layer marked by the tracer. This may be especially true as long as the tracer mark is still near the surface. Then the ground water recharge \( R^e \) will actually be higher than measured by the displacement of the tracer mark. It is, of course, relatively easy to check this possibility by artificial heavy rain spiked with tracer. Sampling of even a limited number of cores after a period of a few weeks will then give a good estimate of the fraction of rain which took a short cut through holes and cracks. A limited number of cores is sufficient since the tracer concentration is smoothed out mostly by lateral diffusion after a period of several weeks. It should be mentioned that lateral molecular diffusion also causes the tracer to penetrate the boundaries of the proving ground resulting in the tracer concentration, within the proving ground but near the boundary, decreasing with time. Another difficulty is possible contamination of the deeper and tracer-free part of a core by material containing tracer from the upper layers.
In conclusion it seems possible to obtain reliable information about evapotranspiration and ground water recharge by experiments of the type mentioned. In order to measure the average ground water recharge over a whole year it would be sufficient to apply the tracer at a favourable date and then sampling one year later. It should be mentioned further that the use of tritium as a tracer is much cheaper and easier (liquid scintillation counting) than deuterium, which we only used as a substitute, having no suitable liquid scintillation instrument at hand in the beginning of this study. In the case of tritium the tracer concentration in the sprinkling water can easily be kept below the maximum permissible concentration in waste water according to ICRP normals.

7.8. The Weizmann Institute of Science and Water Planning for Israel, Israel

7.8.1. Study of input functions of tritium in ground water

7.8.1.1. Statement of the problem

In order to apply the ideas and methods of use of tritium to hydrology, they should be tried first in areas of fairly well-known hydrological characteristics. In this way, the tracer method can be in a way "calibrated". In practice, there is more than just comparison of results in this procedure. Details of mathematical computations, difficulties in estimates of environmental factors like evaporation, and exchange and their time dependence and the frequency and type of sampling, are all examined.

It is expected that the experience gained in these representative basins will be essential in future applications.

7.8.1.2. The tritium input function of the Nahal Oren catchment area

The Nahal Oren catchment area in the Carmel Mountains of Northern Israel, covers an area of 35 km² of fairly steep hills with elevations of 75 m to 555 m above sea level. Its upper part is chalky dolomitic limestone formation, its lower part, permeable crystalline limestone. Both are characteristic of the Cenomanian-Turonian Karst formation of the whole area. The vegetative cover is mainly maqui shrubs with pine forests and pastures in parts of the catchment.

The selection of the area for tritium balance studies was motivated by the fact that a large amount of detailed studies of water balance, soil moisture determination and evaporation exist for that area. It is also conceivable that this area will serve as a representative karst catchment within the programme of representative basins of the IHD.

Of particular interest in constructing the input function is the detailed information on soil moisture withdrawal, following winter recharge and its distribution with depth, for various types of cover. It was determined by a prolonged (30 months) study of moisture content using a neutron moisture meter in 20 holes drilled for that purpose to a depth of 30 ft (SHACHORI et al. 1965)(28). In addition a ground water inventory was maintained, using data on changes in water table, pumping and seepage to the sea. Water velocity determination in that area was made using the single
well time delay method.

Figure 15 shows the rainfall and ground water recharge as deduced from water balance studies. The pronounced fluctuations of about a factor of two in ground water recharge are evident, while rainfall is much more uniform. This relationship is to be expected due to the non-linearity of the rainfall-recharge response function. The detailed structure of the ground water recharge is shown in Figure 16. It is seen that half of the winter rainfall of that year (1963/64) is used for soil moisture replenishment. January to March rains contribute to ground water recharge while later rains again replenish the soil moisture. In computing the concentration of ground water recharge, assumption should be made about exchange with the ambient soil moisture. On general physical grounds it seems that in passing through 30 ft of soil complete exchange should take place. This seems to be born out by lack of stratification with depth in deuterium data.

In the first approximation the weighted average of tritium concentration of rainfall would provide therefore a good value for ground water recharge tritium. A more exact procedure would include stepwise equilibration of incoming recharge, with possible correction for winter evapotranspiration from the top 3 feet only, replenished by the incoming rains. The weighted rain average of tritium content is shown in Fig. 20. This procedure, while shown to be satisfactory in this case, should not be used, however, without detailed justification. Pronounced run-off (not existing in this case) in the later part of the rain season could affect considerably this weighting procedure.

Only scarce ground water data is available for that region to date. Those shown on Fig. 20 seem to indicate, however, the predominance of long transit times in the aquifer. Detailed yearly analysis of input functions, as demonstrated above is planned now for the whole period covered by the hydrological data.

7.8.1.3. "Determining the Porosity and Permeability of a Stratified Aquifer with the Aid of Radioactive Tracers."

This report will be published by J. Geoph. Res. 1966.

GENERAL

It has been emphasized by several authors (30, 31) that in hydrological investigations the greatest advantage of tracing methods is that besides verifying results obtained by independent methods, tracing methods provide information otherwise unobtainable. The comparison of tracing methods with conventional methods for the determination of aquifer characteristics can be satisfactorily made in such experimental well-fields which are as homogeneous as possible, and whose properties are fairly well-known.

In the present report a tracing technique for determining the porosity and the different permeabilities of a multilayered aquifer is described.
The permeabilities of a multilayered aquifer, whose layers are separated by impervious boundaries, are easily determined by using standard pumping interference tests. However, in the case of multilayered aquifers, whose layers are not separated each from the other, pumping techniques fail, and resort to other investigative methods must be taken. The method chosen in the present case is a tracing method, in which labelled radioactive salt is used as tracer.

**THEORETICAL**

Let us consider the case of a two-layered aquifer. It has been assumed that the boundary between the two layers is leaky. The aquifer is penetrated by wells of different depths and perforations (Fig. 17).

A radioactive tracer is first injected into the upper layer of the aquifer through the penetrating Well No. 1. Pumping is then commenced at the fully penetrating Well No. 3, and the activity of the pumped water is continuously recorded until all the injected tracer is pumped out.

Assuming a cylindrical symmetry in pumping, the peak activity would be obtained after pumping a volume of $(V_p)_1$:

$$(V_p)_1 = \varphi R_1^2 b_1 n_1 Q_1$$

where $R_1$ is the distance between the injection and pumping wells; $b_1$ the thickness of the layer; $n_1$ its porosity; $Q_1$ the pumping rate; and $Q_1$ the partial discharge rate from the upper layer.

The tracer is then injected into the well having open perforations in its lower part only (No. 2). For the peak volume of this experiment we obtain:

$$(V_p)_2 = \varphi R_2^2 b_2 n_2 Q_2$$

If complete leakage exists between the two layers, the piezometric surface will be identical for both, and the partial discharge rates from each layer will be directly proportional to its transmissivity $(T)$. From eq. (1) and eq. (2) we have:

$$(V_p)_1 = \varphi R_1^2 b_1 n_1 T_1$$

$$(V_p)_2 = \varphi R_2^2 b_2 n_2 T_2$$

and generally:

$$(V_p)_i = \varphi R_i^2 b_i n_i T_i$$
Dividing (3) by (4) gives:

\[
\frac{(Vp)_1}{(Vp)_2} = \frac{R_1^2 b_1 n_1 T_2}{R_2^2 b_2 n_2 T_1}
\]

Recalling that \(T_1 + T_2 = T\), and assuming equal porosities, we obtain from eq. (6) the following relationship for \(T_1\) and \(T_2\):

\[
T_1 = \frac{T}{\left(\frac{(Vp)_1}{(Vp)_2} \cdot \frac{R_2^2 b_2}{R_1^2 b_1}\right) + 1}
\]

\[
T_2 = \frac{T}{\left(\frac{(Vp)_2}{(Vp)_1} \cdot \frac{R_1^2 b_1}{R_2^2 b_2}\right) + 1}
\]

There is no doubt that the porosities of the two layers are not identical, but for all practical purposes and approximations it can be assumed that differences in porosities of neighbouring layers will, as a rule, be considerably smaller than possible differences in their transmissivities.

Thus, if \(R_1\) and \(R_2\) are known from direct measurements, \(b_1\) and \(b_2\) from geological sections, \((Vp)_1\) and \((Vp)_2\) from experimental results and \(T\) from pumping tests, the values of \(T_1\) and \(T_2\) can be calculated from experimental results.

Knowing the values of the transmissivities \((T_1\) and \(T_2\)) and recalling that \(T = Kb\) (\(K\) being the permeability), it is now simple to calculate the permeability values.

It should be noted that eq. (1) to eq. (8) are also valid for the case of fully penetrating injection wells. In this case \(R_1\) is equal to \(R_2\).

The same procedure can now be followed for any number of layers.

**Experimental**

The experimental work was carried out at the Haifa Bay Experimental Field (32). The field lies over a phreatic and shallow aquifer covered by sand dunes. The aquifer is directly replenished by rainfall, which is the only water source feeding it. Salinity is low (30-80 mg chlorides per litre). The average annual precipitation is about 600 mm. A marshy clay layer which rises gradually, and reaches ground level some 1 to 2 km east of the experimental field, serves as an impervious boundary.
A typical lithological cross section is as follows:

<table>
<thead>
<tr>
<th>Depth</th>
<th>Strata</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 3 metres</td>
<td>Fine dune sand</td>
</tr>
<tr>
<td>3 - 9 &quot;</td>
<td>Soft calcareous sandstone with sand</td>
</tr>
<tr>
<td>9 - 15 &quot;</td>
<td>Grey sand and sandstone rich in marine fauna</td>
</tr>
<tr>
<td>15 &quot;</td>
<td>Black clay</td>
</tr>
</tbody>
</table>

The experimental field consists of forty observation wells and two pumping and injection wells. The experiment reported took place between the observation wells 13 and 13A, which served for the pulse injection, and the pumping well P.R.6. Observation wells 15 and 15A served for intermittent sampling only. Fig. 18 shows the layout and the geological section between the pertinent wells.

Numerous preliminary pumping tests (32) were carried out. From the results the following aquifer parameters were calculated: hydraulic permeability \( (K) = 25 \text{ m/day} \), thickness of the aquifer \( (b) = 10 \text{ m} \), transmissivity of the aquifer \( (T) = 250 \text{ m}^2/\text{day} \), storativity \( = 13 \% \). The aquifer has a natural westward gradient \( (J) \) of 1 - 1.5 \%.

The radioactive tracer used was \( ^{60}\text{Co} \) in the form of potassium hexacyanocobaltate \( K_3^{60}\text{Co} (\text{CN})_6 \) (33). The carrier concentration in the injection pulse was about 5 mg per cu.m. The detection system used, termed W-11 (manufactured by Elron Electronic Industries Ltd., Israel), is based on a large volume sample detection (34). The sensitivity of the detection system (10 standard deviations) was \( 3 \times 10^{-5} \text{ uc/ltre} \). Since the maximum permissible concentration for \( ^{60}\text{Co} \) in drinking water is 0.5 \( \mu \text{c/ltre} \) (35), it is obvious that due to the high sensitivity of the detection system, the experiments were not limited by any health hazard restrictions.

Two experiments termed Tests A and B were made. Each consisted of a pulse injection at an observation well (13 or 13A), pumping at the Well P.R.6, and intermittent sampling at the observation wells 15 and 15A. The tracer was injected through a 1" pipe lowered to the perforation depth. It was then displaced from the borehole by injecting fresh water.

The injection data is summarized in the following table:

**TABLE - INJECTION DATA FOR TESTS A AND B**

<table>
<thead>
<tr>
<th>Test</th>
<th>Injection Well</th>
<th>Injected Volume m³</th>
<th>Rate of Injection m³/h</th>
<th>Displacing Volume m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>13</td>
<td>0.61</td>
<td>1.93</td>
<td>0.02</td>
</tr>
<tr>
<td>B</td>
<td>13A (upper)</td>
<td>1.25</td>
<td>1.25</td>
<td>0.30</td>
</tr>
</tbody>
</table>
The pumping well, 15 m away from the injection wells, was discharged at an average rate of 36.3 m$^3$/h (min. = 35 m$^3$/h, max. = 42 m$^3$/h). Pumping was commenced a week before the injection, in order to reach relatively steady state conditions.

The following table summarizes the measured average water levels at various wells, as well as the bottom levels for each layer.

**TABLE - WATER LEVELS AND LITHOLOGICAL DATA**

<table>
<thead>
<tr>
<th>Well No.</th>
<th>Distance from P.R.6 (m)</th>
<th>Water Level above M.S.L. (m)</th>
<th>Position of Leaky Boundary above M.S.L. (m)</th>
<th>Bottom Position above M.S.L. (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>15.0</td>
<td>+ 3.30</td>
<td>- 0.2</td>
<td>- 7.0</td>
</tr>
<tr>
<td>13A</td>
<td>15.0</td>
<td>+ 3.31</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>17</td>
<td>10.0</td>
<td>+ 2.99</td>
<td>- 0.3</td>
<td>- 6.0</td>
</tr>
<tr>
<td>17A</td>
<td>10.0</td>
<td>+ 2.99</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>7.5</td>
<td>+ 2.80</td>
<td>- 0.2</td>
<td>- 7.0</td>
</tr>
<tr>
<td>15A</td>
<td>7.5</td>
<td>+ 2.79</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>P.R.6</td>
<td>-</td>
<td>+ 0.30</td>
<td>- 0.3</td>
<td>- 7.0</td>
</tr>
</tbody>
</table>

*Note* After correction for the hydraulic friction loss at the well's screen; measured: - 0.70 m above M.S.L.

A weighted average of 10.3 m for the thickness of the aquifer is obtained from the above data (6.8 m for the lower layer and 3.5 for the upper one). The cylindrical bulk volume between observation well 13 (or 13A) and P.R.6 is 7,260 m$^3$.

The observation wells 15 and 15A, which are located on the line connecting Well 13 and P.R.6 (Fig. 18), were sampled in order to collect supplementary data on the progress of the injected pulse towards the pumping well. The samples, 100 ml each, were extracted by bailing following a preliminary mixing of the water in the well's pipe. The samples were measured by a low-level gamma monitor, the Sciron System (36).

**RESULTS AND DISCUSSION**

The dimensionless activity $C/C_p$ ($C_p$ = peak concentration or activity) as a function of the square root of pumped water ($\sqrt{V}$) at the pumping well P.R.6 is shown in Fig. 19.

The activity is described as a function of $\sqrt{V}$ instead of $V$, in order to display the output activity as a function of the radius $r$ (31), by using the relationship
where "r" is the corresponding radius of the pumped volume "V". The peak volume "V_p" is determined as that corresponding to the centre of the full width at half the peak intensity (34).

The measured breakthrough curves at the observation wells 15 and 15A are shown in Fig. 20. An outstanding feature of these curves is that no activity was recorded at Well 15A when the injection took place at Well 13 (Test A), or at Well 15 after injection at Well 13A (Test B). The basic assumption that stream lines were horizontal, and no intermixing occurred between the two layers has been fully confirmed, at least within the radial distances of R = 15 m and R = 7.5 m.

The following table gives the measured peak volume (V_p) of pumped water at tests A and B (Fig. 19).

<table>
<thead>
<tr>
<th>Test</th>
<th>Injection Well</th>
<th>V_p - Peak Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>First Peak</td>
</tr>
<tr>
<td>A</td>
<td>13</td>
<td>1550</td>
</tr>
<tr>
<td>B</td>
<td>13A</td>
<td>4170</td>
</tr>
</tbody>
</table>

According to the recorded peaks, the aquifer investigated consists of at least four layers. In order to determine the transmissivity (T), the permeability (K), and the thickness (b) of each layer, the following procedure was adopted:

1) Using eqs. (7) and (8), where equal porosities were assumed, the average transmissivities, "T₁" and "T₂", of the two general layers corresponding to observation wells 13A and 13 respectively, were determined.

From the data, using the average peak volumes (Table XXIII) for Tests A and B, we have:

(upper layer)

\[
T_1 = \frac{T}{\left[ \frac{(V_p)_1}{(V_p)_2} \frac{R_2}{R_1} \frac{b_2}{b_1} \right] + 1} = \frac{250}{\left[ \frac{1500}{1500} \frac{15}{3.5} \right] + 1} = 40.5 \text{ m}^2/\text{day}
\]

(lower layer)

\[
T_2 = T - T_1 = 250 - 40.5 = 209.5 \text{ m}^2/\text{day}
\]
(2) Using either eq (3) or (4), the average porosity (assumed to be identical for all layers of the aquifer) was determined.

From the data:
\[
\bar{\eta} \approx n_1 = \frac{(Vp)_1 T_1}{n^2 b_1 T} = \frac{5200 \times 40.5}{\eta \times (15)^2 \times 3.5 \times 250} = 34 \%
\]

(3) The permeabilities of the four layers were determined according to eq. (5):

\[
(Vp)_i = \eta R^2 \frac{b_i n_i T}{(Vp)_i}
\]

or:

\[
K_i = \frac{\eta R^2 n_i T}{(Vp)_i}
\]

(10)

Using the previously calculated porosity, the following values were obtained from the data: \(K_1' = 14.4 \text{ m/day}, K_1'' = 9.7 \text{ m/day}, K_2' = 25.6 \text{ m/day} \) and \(K_2'' = 38.8 \text{ m/day}\).

\(K_1', K_1'', K_2', K_2''\) are the corresponding permeabilities of the first and the second peak volumes of tests A and B, respectively.

It is recalled that the average permeabilities of the two general layers are:

\[
K_1 = \frac{T_1}{b_1} = \frac{40.5}{3.5} = 11.6 \text{ m/day}
\]

\[
K_2 = \frac{T_2}{b_2} = \frac{209.5}{6.8} = 30.8 \text{ m/day}
\]

where \(b_1\) and \(b_2\) are the thicknesses of the upper and the lower layer respectively, as measured from the geological cross section.

(4) The thicknesses of the four layers were obtained by:

\[
b_1' = \frac{K_1 - K_1''}{K_1' - K_1''} b_1
\]

(11)

\[
b_1'' = \frac{K_1' - K_1''}{K_1'' - K_1'} b_1
\]

(12)
where the thicknesses $b_1', b_1''$ and $b_2', b_2''$ correspond to the permeabilities $K_1', K_1''$ and $K_2', K_2''$, respectively.

From the data, and using eqs. (11) to (14) we have $b_1' = 1.4$ m, $b_1'' = 2.1$ m, $b_2' = 2.7$ m, $b_2'' = 4.1$ m.

By examining the geohydrological cross section (Fig. 18), the layers $b_1''$ and $b_2''$ can probably be identified as the lower (grey sand with small muddy-black pebbles) and the upper layer (grey sand with shale fragments), respectively.

Fortunately, we have additional independent evidence which can support and confirm the above assumptions and calculations. Numerous analyses of chloride content in water samples taken from various wells at the experimental field showed a significant difference in the chloride content of the two layers ($C_1 = 25$ ppm at shallow wells and $C_2 = 50$ ppm at deep wells). The chloride content of the pumped water at P.R.6 shows some weighted average between the two ($C = 45$ ppm). This has been expected since P.R.6 is a fully penetrating well, perforated at both layers.

The chloride balance requires that (Fig. 21)

$$C \cdot Q = C_1 \cdot Q_1 + C_2 \cdot Q_2$$

or

$$C \cdot T = C_1 \cdot T_1 + C_2 \cdot T_2$$

From the data, and using eq. (16) we have:

$$T_1 = \frac{C - C_2}{C_1 - C_2} \cdot T = \frac{45 - 50}{25 - 50} \times 250 = 50 \text{ m}^2/\text{day}$$

$$T_2 = T - T_1 = 250 - 50 = 200 \text{ m}^2/\text{day}$$

The last values of "$T$" are in close agreement with those calculated before and support the assumption that the porosities are about equal in the two layers.

**SUMMARY AND CONCLUSIONS**

The transmissivities and permeabilities of a heterogeneous stratified aquifer were determined. It is shown that tracer techniques are applicable and facilitate the study of the microstructure of shallow aquifers.
The advantage of radioactive tracers used in the experiments described lies in the extreme sensitivity of the detection system. This property enables the introduction of minute quantities of tracer which definitely cannot change the natural flow properties of the aquifer.

The findings were supported by chemical analyses and by classical pumping tests. The report purports to show the usefulness of applying various techniques, among them the radioactive tracer, for the determination of certain aquifer parameters.

7.9. University of Groningen, Netherlands

7.9.1. Age Distribution of Ground Water in an Open Aquifer

Consider a homogeneous aquifer with a constant depth which is being recharged by precipitation over the whole area and in which the water is flowing outwards from a water shed. According to Darcy's law the horizontal flow velocity

$$v = \frac{dl}{dt} = K \frac{dh}{dl}$$

is constant over any vertical profile.

This velocity, however, increases with the distance "$l$" from the watershed because the intake area increases faster than the section area through which the water must pass.

The flow-rate "q" through any section "S" is equal to the total amount of effective rainfall recharge "W" over the area "a" upstream from "S" (see Fig. 21).

$$q = W \cdot a$$

Now "q" is the volume of water \(dV = \phi \cdot H \cdot da\) passing through "S" in time "\(dt\)".

\(\phi = \) fractional pore volume
\(H = \) total depth of aquifer

so that

$$\phi \cdot H \cdot da \cdot dt = W \cdot a$$

integrating,

$$t = \frac{\phi H}{W} \cdot \ln \frac{a}{a_1}$$

This is the time necessary for the front to pass from point "$1_1$" to point "$1$".
To determine the age of the water at a height \( h \) above the base (depth \( H - h \)) at point "1" we consider the streamline starting at the surface \( h_1 = H \) at point "1" and passing through this point.

The recharge \( W \times a \) collected above point "1" must pass through the surface "S" so that

\[
W \times a = q = v \cdot \phi \cdot S
\]

While the recharge \( W \times a_1 \) collected above point "1" passes through the surface \( h_1 \) and

\[
W \times a_1 = v \cdot \phi \cdot \frac{h}{H} \cdot S
\]

therefore

\[
\frac{a}{a_1} = \frac{H}{h}
\]

replacing in eq. (1):

\[
t = \frac{\phi H}{W} \ln \frac{H}{h}
\]  

Eq. (2) gives the age of the water at point \((1, h)\) and as it does not depend on "1". It follows that the vertical age distribution is independent of the distance from the watershed. Also the age increases logarithmically with depth.

The characteristic age at half-depth is given by:

\[
t_{1/2} = \frac{\phi H}{W} \cdot \ln 2 = 0.69 \frac{\phi H}{W}
\]

The average age:

\[
\bar{t} = \frac{\phi H}{W}
\]

Eqs. (1) and (2) apply to any horizontally uniform geometry. The two cases normally encountered are (i) Parallel flow where the intake starts from a straight ridge and the streamlines run horizontally parallel and (ii) Radial flow where the watershed is represented by a point and the streamlines run radially outwards.

7.9.2. Application

An opportunity to demonstrate the age stratification by \(^{14}\text{C}\) dating presented itself on the Dutch island of Schiermonnikoog where the Intercommunal Waterworks in Leeuwarden have recently sunk a series of observation wells. Samples were collected from different depths in two wells on the western end of the island where the ground water flow is approximately radial and the depth of the fresh water body is limited and nearly constant. The results are shown in Fig. 22.
The more inland well Sch 22 gave a linear decrease of $^{14}C$ content with depth (Fig. 23) and an approx. logarithmic increase of the apparent age. The age at half-depth is 130 yrs. In the coastal well Sch 13 the stratification is not so clear-cut, but there is nevertheless a general increase of age with depth.

Calculation of the age by eq. (2) depends strongly on the value assumed for the effective recharge rate. Using

$$W = 0.3 \text{ m/a}, \varphi = 0.5 \text{ and } H = 60 \text{ m}$$

we find

$$t_{1/2} = 70 \text{ yrs.}$$

7.10. Discussion

Emphasis was put on the following points, which are elucidated in the working papers.

(a) There is a marked influence on isotopic composition of rain recharge as a result of passage through the unsaturated zone.

(b) Although some findings in Central Europe point to the possibility of using the average yearly composition as the representative input composition, this is not necessarily so in other regions. In semi-arid zones recharge to ground water occurs sometimes only once in a few years and even then it may represent a different composition than expected from precipitation values.

(c) Study of these phenomena (rate, quantity and composition of recharge to ground water in relation to precipitation, evaporation and transpiration) should be initiated in as many regions as possible. It is best facilitated by lysimeters or in experimental basins.

(d) Many phreatic aquifers show stratification of $^3$H and $^{14}C$. This creates a problem of reference age for the aquifer or the profile. It was suggested to use the value at half depth as a representative value.

(e) Even if flow lines are parallel in the bulk of the aquifers, lateral dispersion over thousands of years should equalize many differences expected in stratified flow.

8. TRITIUM AND CARBON-14 CHRONOLOGY

8.1. Centre d'Etudes Nucléaires, Grenoble, France

At present the group has two sets of electrolytic cells for enrichment of tritium and a TRICARB liquid scintillation counter. Consideration is being given to the construction of a large liquid scintillation counter capable of measuring a 30 ml sample with a concentration of 400 T.U. in 6 hours. A gas counter manufactured by Philips is being installed.
These facilities are being applied to the measurement of tritium in precipitation of 26 national meteorological stations. It is also intended to use tritium as a new parameter of water in an extension of the Schoeller-Berkaloff method.

In order to solve a problem of communication between a river and springs associated with the construction of a dam at Verdon-Asturby, tritium is being measured in monthly samples of rain, river water and springs.

8.2. Faculty of Science, University of Bordeaux, France

At present three laboratories are analysing about 100 samples per month. Precipitation measurements are not made on the basis of a monthly average, but samples are taken at the start, middle, and end of a shower. It has been found that on the west coast of France rain originating from the Atlantic had a tritium concentration of 150 - 200 T.U., while the concentration was 1 700 T.U. at the commencement of a shower coming from the east. In March 1965 a rainstorm coming from the north had a concentration of 500 T.U. at the beginning and a concentration of 170 T.U. at the end.

The tritium concentration of the M. Cenis reservoir has been studied since the end of 1963. A parallelism was found between the tritium concentration of water near the bottom of the lake and that of water from nearby springs. In contrast to the stratification found in this reservoir, none was found in a lake (23 m deep) near Bordeaux.

8.3. Physical Laboratory, University of Iceland, Reykjavik, Iceland

A systematic survey is being made of the deuterium and tritium concentration of precipitation and of water from cold and hot springs. A number of the measurements date back to 1960. The tritium concentration of the hot springs indicate old water. So far almost all values are less than 5 T.U. The concentration of the cold water supplies from Reykjavik, Hafnarfjörður and Keflavik are much higher, though different for the three supplies. All are considerably lower than the values for tritium in precipitation. It is hoped that by continuation of this survey that it will be possible to correlate the seasonal variations with those for rain in a given year.

8.4. US Geological Survey, Washington, D.C., USA

Carbon-14 activity was determined in samples of ground water obtained from the principal artesian aquifer in Florida. From the data the apparent age was estimated of water from a series of wells progressively down-gradient on the piezometric surface. Relative ages over a distance of about 85 miles indicated a velocity of ground water movement in agreement with that calculated from Darcy's law. Details of this study have been published. (37)
Radioactive tracers have been used to study the movement of water in peat which is an organic product formed from decayed vegetation. It is found in many parts of the world, particularly in wet climates. Water movement in peat is of interest when considering use of the peat for fuel, use of the land for agriculture or use of the extensive upland deposits of peat as sources of water supply or base load flow or rivers.

An investigation has been undertaken in a peat drainage bog on a hillside in Yorkshire. The bog arose from a spring and extended down the hillside with a slope of 8°. The peat depth was about 100 cm. An injection of 20 mc iodine-131 (with carrier) and 200 mc tritium was made at 50 cm depth. The movement was proved to be very slow and a full survey of the bog was made in three dimensions after 18 months. Samples were taken at 23 cm (9 inch) intervals of depth in a pattern of 80 holes.

Results showed that the tracer had spread over the whole vertical depth of the bog and the average lateral movement was 18 feet in 18 months. Much of the tracer had been transported to the surface where it was rapidly removed by surface water run-off. This investigation will be more fully published later.

A similar investigation in a raised bog (Hochmoor) has shown a slower movement of water. This investigation is associated with land drainage and leakage of water into or out of an experimental catchment.

$^{14}$C age determinations of water samples have been performed for several years. The group has attempted to solve remaining problems by statistical investigation. Some of these results were reported during the VIth International $^{14}$C and Tritium Dating Conference in Pullman, 1965. (38)

Reliable age determination of ground water can be expected only when the aquifer is a closed system and is in equilibrium according to the equation:

$$\text{CaCO}_3 + \text{H}_2\text{O} + \text{CO}_2 \rightleftharpoons \text{Ca(HCO}_3^-)_2$$

Moreover, the carbon dioxide is assumed to be purely recent-biogenic, the calcium carbonate purely fossiliferous marine.

MÜNNICH, VOGEL and co-workers (39) have demonstrated the importance of filtration through the soil zone in establishing the isotopic composition of the carbonate input. They have also suggested the use of $^{13}$C to correct for exchange with carbonate minerals in the ground water system.
The \(^{14}\text{C}\) laboratory has undertaken to find statistical evidence of the reliability of the MUNNICH model by investigating the carbonic acid equilibrium, by measuring the \(^{13}\text{C}\) values and by determining the specific \(^{14}\text{C}\) content of a number of water samples. For this purpose 36 water samples were taken from sand and gravel layers of the Quarternary and the Tertiary and several ground water horizons in Niedersachsen. The content of \(\text{CO}_2\) and bicarbonate was determined at the sampling site. In all cases, the hydrological situation was known in detail.

For comparison, 25 more water samples were taken from springs in consolidated rocks, from crevice waters and from pits in the same area, and were analysed as above.

The procedure involved the following steps: Determination of the carbonate and bicarbonate by chemical methods. Collection of the carbonate species by precipitation from 60 litre sample using barium salts. Counting of the carbon as acetylene at a pressure of 1 atm. in an 0.81 l counter with background of 3.3 cpm. Determination of \(^{13}\text{C}\).

The reproducibility of preparation is estimated at \(\pm 0.7\%\) but the \(^{13}\text{C}\) content of Solnhofer limestone was found to vary as much as \(\pm 2.5\%\).

On the basis of the several sources of carbonate ion species involved in the dissolution reaction the following equation was developed to represent the relation between delta \(^{13}\text{C}\) values and relative concentrations of carbonate species in the water at equilibrium.

\[
\varphi = \frac{\delta}{\delta_o} = \frac{1/2(\text{HCO}_3^-) + (\text{CO}_2)}{(\text{HCO}_3^-) + (\text{CO}_2)}
\]

(1)

\(\varphi\) = measured deviation from Solnhofer limestone standard

\(\delta_o\) = deviation for biogenic carbon

In Fig. 24 \(^{13}\text{C}\) values are plotted against \(\varphi\) values. Soft waters with \(\text{HCO}_3^-\) content below 2 mM \(\text{HCO}_3^-\) per litre are marked by crosses, samples from aquifers in consolidated rock by solid circles and from aquifers in unconsolidated materials by open circles. The solid line represents the theoretical curve according to equation (1) using \(\delta_o = -25\%\). From 185 determinations of biogenic \(\text{CO}_2\) samples a 95.5\% standard deviation for \(\delta_o\) of \(\pm 5.0\%\) was established. The two dotted lines indicate the 95.5\% level.

The graph appears to apply satisfactorily to soft waters, and most waters from aquifers in consolidated rock, 51 samples from unconsolidated formations gave results outside the \(\varphi\) interval. These samples were found to represent waters that had filtered down through peat in the upper layers of the soil.

At present the concept of the \(\varphi\) criterion and its application to the correction of \(^{14}\text{C}\) apparent ages is under investigation in laboratory column tests. It is not yet satisfactory for the correction of measured ages.
The results obtained with $^{14}$C dating of ground waters are briefly reviewed as follows: No measurement has given an age older than 10,000 years even at depth below 100 metres. The correlation of the depth at which the sample was taken with the apparent and corrected $^{14}$C concentrations is shown in Fig. 25, (based on 70% organic carbon in recharge water). It is found that $^{14}$C content of ground waters increases in the direction away from the North Sea and away from the valley of the Elbe. This indicates that the direction of regional ground water flow is toward the North Sea and the Elbe.

Tritium investigations are underway to identify possible mixing of recent water into the ground water systems.

8.7. Discussion

KNUTSSON reported on the use of tritium dating to study seepage in a mine in northern Sweden. One suspected source of seepage water was a lake. However, investigations using salt as a tracer gave no conclusive results. A number of samples were taken for tritium analysis and the following results obtained:

- Lake outside area: 1,300 T.U.
- Melt water and lake over mine: 900 T.U.
- Tunnel No. 370: 620 T.U.
- Tunnel No. 420: 90 T.U.
- Ground water in sandstone: 35 T.U.

It was therefore concluded that seepage water in Tunnel No. 370 originated from the lake over the mine and the water in Tunnel No. 420 originated from the ground water. Attempts will now be made to stop the seepage from the lake.

With regard to the use of $^{14}$C dating of ground water HANSHAW presented an exchange model which suggests that even under conditions which are most favourable for exchange, the $^{14}$C ages corrected by $^{13}$C are reliable.

9. THE INTERNATIONAL HYDROLOGICAL DECADE AND EXCHANGE OF INFORMATION

The representative of UNESCO summarized the objectives of the decade programme and drew the attention of the working group to a number of sections of the programme in which isotope techniques are applicable. It was emphasized that the occasion of the International Hydrological Decade presented an excellent opportunity for the introduction of isotope techniques. The members of the working group were encouraged to enter into collaborative studies with hydrologists in various decade projects.

With regard to improved dissemination of scientific and technical information some discussion took place on ways in which this could be done. TIMBLIN described the method used in the Bureau of Reclamation in which senior engineers and scientists prepare their scientific profile of key...
words. Technical publications are indexed with key words according to a standard thesaurus and automatically compared by electronic data processing machines with professional interest profiles. When the key words for an article match a profile, the scientist is automatically provided with a card showing the key words on one side and the abstract on the reverse side. The Federal Council for Science and Technology is considering a recommendation to establish a national center for collection, storage, dissemination and retrieval of information in the water resources field. It was suggested that the Agency might consider initiating a program for adoption of unified criteria for the preparation of abstracts and the addition of key words for articles published by the Agency.

The members of the working group welcomed the convening of such meetings and were in favor of the preparation of a newsletter summarizing the work of different groups.

10. CONCLUSIONS

At the end of the meeting, the members of the working group briefly summarized their ideas on the direction to which work should be orientated under each of the subjects discussed.

10.1. Flow Gauging

a) Development of practical methods for determining mixing distance.

b) Theoretical studies of diffusion in all three dimensions, together with model studies.

c) Comparison of different isotope methods with standard hydrological methods.

d) Emphasis should be placed on the measurement of large flow rates.

The point of view of the hydrologist was expressed in saying that the main problem at the present time is one of technology. The method must be simple for use by non-professional personnel, health and safety considerations are important and also the cost of the method.

10.2. Sediment Transport

a) Emphasis should be placed on quantitative measurement.

b) In coastal applications there is a need to study the effect of tides, swell etc., on the coast.

c) A study of labelling fine sediment.

d) Research should be undertaken to ascertain whether the interpretation of the entire sand movement is possible by measuring the movement of tracer particles representing the course of bed material.

e) Improved methods for measuring the depth of tracer mixing.
f) Studies of the depth of mixing in the presence of dunes and ripples, both experimentally and using mathematical models of a hypothetical mixing mechanism.

  g) The accumulation of further data on the labelling of silts with longer lived (1 month or so) radioisotopes.

  h) Standardization of procedures for checking the fixation of the labelling element.

10. 3. **Ground Water Velocity and Direction**

  a) A study of the limits of borehole methods including the best form of borehole construction, the effects of packers and seals or suited to tracer applications.

  b) Comparison of isotope measurements with pumping tests.

10. 4. **Tritium and $^{14}$C Chronology**

  a) Investigations should now be made on larger scale studies.

  b) Study of the exchange effect in $^{14}$C studies.

  c) Joint collaborative studies between isotope methods and hydrological methods.
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Mr. W.Z. Wood
<table>
<thead>
<tr>
<th>Expt. No.</th>
<th>Tracer</th>
<th>Quantity</th>
<th>Mode of application</th>
<th>Measurements with</th>
<th>Tracer dyes</th>
<th>Propeller</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>Radioactive tracers</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Average From 200 l composite sample and 100 l flow container</td>
<td><strong>Enrichment by Adsorption on ion-exchange resin</strong></td>
<td><strong>Precipitation</strong></td>
</tr>
<tr>
<td>2</td>
<td>131I</td>
<td>29 mCi</td>
<td>inst.</td>
<td>15.5</td>
<td>15.3</td>
<td>19.8</td>
</tr>
<tr>
<td></td>
<td>Uranine</td>
<td>20 g</td>
<td>cont.</td>
<td></td>
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<tr>
<td></td>
<td>131I</td>
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<td>inst.</td>
<td>15.3</td>
<td>15.8</td>
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<tr>
<td>3</td>
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<td>27 mCi</td>
<td>inst.</td>
<td>15.2</td>
<td>17.1</td>
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<td>4</td>
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<td>19.8</td>
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<tr>
<td>5</td>
<td>131I</td>
<td>26 mCi</td>
<td>inst.</td>
<td>15.7</td>
<td>16.3</td>
<td>17.5</td>
</tr>
<tr>
<td></td>
<td>Rhodamine B extra</td>
<td>10 g</td>
<td>inst.</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>6</td>
<td>131I</td>
<td>30.5 mCi</td>
<td>cont.</td>
<td>15.0</td>
<td>14.7</td>
<td>15.9</td>
</tr>
<tr>
<td></td>
<td>Rhodamine B extra</td>
<td>100 g</td>
<td>cont.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Accuracy of the Q values is about 3-5%  
Inst. = instantaneous application  
Cont. = continuous application

Table I  Results of the first Krüner experiment (15-18 September 1964). The figures refer in each case to the flow (in m³/s, calculated by the method in question
<table>
<thead>
<tr>
<th>Sampling Place</th>
<th>Method</th>
<th>Flow Q (m³/s)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Upper gauging station</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left bank</td>
<td>Float sampler</td>
<td>1010</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Composite ladle sample</td>
<td>970</td>
<td></td>
</tr>
<tr>
<td>Middle</td>
<td>Ladle samples from surface</td>
<td>665</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ladle samples at depth</td>
<td>665</td>
<td></td>
</tr>
<tr>
<td>Right bank</td>
<td>Ladle samples</td>
<td>730</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>805</td>
<td></td>
</tr>
<tr>
<td><strong>Lower gauging station</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left bank</td>
<td>Ladle samples</td>
<td>675</td>
<td></td>
</tr>
<tr>
<td>Middle</td>
<td>Ladle samples</td>
<td>615</td>
<td></td>
</tr>
<tr>
<td>Right bank</td>
<td>Composite ladle sample</td>
<td>695</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>660</td>
<td></td>
</tr>
</tbody>
</table>

Table II  Results of the second Danube experiment (23 Oct. 1964) giving calculated flows (Q). The figure furnished by the Kachlet power plant for purposes of comparison is 640 m³/s. The results have been rounded off.
<table>
<thead>
<tr>
<th>Expt. No.</th>
<th>Tracer</th>
<th>Quantity</th>
<th>Mode of application</th>
<th>Radioactive tracers</th>
<th>Tracer dyes</th>
<th>Propeller</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>100 l flow container</td>
<td>200 l composite sample</td>
<td>Enrichment by precipitation</td>
<td>Float sampler</td>
<td>Ladle samples</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Left</td>
<td>Middle</td>
<td>Right</td>
</tr>
<tr>
<td>1</td>
<td>$^{82}$Br Rhodamine B extra</td>
<td>11.4 mCi 13.4 g</td>
<td>inst.</td>
<td>inst.</td>
<td>17.1</td>
<td>17.2</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Rhodamine B extra</td>
<td>126 g</td>
<td>cont.</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>$^{82}$Br Uranine</td>
<td>9.9 mCi 29.7 g</td>
<td>inst.</td>
<td>cont.</td>
<td>17.2</td>
<td>16.9</td>
<td>19.1</td>
</tr>
<tr>
<td>4</td>
<td>$^{131}$I Uranine</td>
<td>28.7 mCi 2.24 g</td>
<td>inst.</td>
<td>inst.</td>
<td>16.9</td>
<td>-</td>
<td>19.5</td>
</tr>
<tr>
<td>5</td>
<td>$^{131}$I Sulfonrhodamine</td>
<td>16.3 mCi 70.1 g</td>
<td>inst.</td>
<td>inst.</td>
<td>17.2</td>
<td>-</td>
<td>17.4</td>
</tr>
<tr>
<td>6</td>
<td>$^{131}$I Uranine</td>
<td>28.0 mCi 9.15 g</td>
<td>inst.</td>
<td>inst.</td>
<td>17.2</td>
<td>-</td>
<td>19.3</td>
</tr>
</tbody>
</table>

inst. = instantaneous application  
cont. = continuous application

**Table III** Results of the second Krüner experiment (26 and 27 November 1964). The figures refer in each case to the flow (in m³/s) calculated by the method in question.
<table>
<thead>
<tr>
<th>Category</th>
<th>Rock or Soil</th>
<th>Permeability coefficient</th>
<th>General characteristic</th>
<th>General characteristic</th>
<th>General characteristic</th>
<th>General characteristic</th>
<th>General characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Clays, loams, shales, solid igneous rocks, marbles</td>
<td>0 \times 10^{-5}</td>
<td>-</td>
<td>4 \times 10^{-4}</td>
<td>4 \times 10^{-4}</td>
<td>-</td>
<td>4 \times 10^{-4}</td>
</tr>
<tr>
<td>II</td>
<td>Cracked shales, recent loams, slightly cracked igneous rocks</td>
<td>10^{-5}</td>
<td>-</td>
<td>4 \times 10^{-3}</td>
<td>4 \times 10^{-3}</td>
<td>-</td>
<td>4 \times 10^{-4}</td>
</tr>
<tr>
<td>III</td>
<td>Sands and very fine loamy sands, cracked rocks</td>
<td>10^{-4}</td>
<td>-</td>
<td>4 \times 10^{-2}</td>
<td>4 \times 10^{-2}</td>
<td>-</td>
<td>4 \times 10^{-3}</td>
</tr>
<tr>
<td>IV</td>
<td>Fine silty sands, old cracked rocks</td>
<td>10^{-3}</td>
<td>Slightly permeable</td>
<td>-</td>
<td>4 \times 10^{-4}</td>
<td>100 \pm 10</td>
<td>200 \pm 20</td>
</tr>
<tr>
<td>V</td>
<td>Fine and middle slightly loamy sands, fine sands, middle sands, slightly cemented sandstones</td>
<td>10^{-2}</td>
<td>-</td>
<td>4 \times 10^{-3}</td>
<td>10 \pm 1</td>
<td>10 \pm 2</td>
<td>1 \pm 0.1</td>
</tr>
<tr>
<td>VI</td>
<td>Coarse, uniform slightly loamy sands, fissured rocks</td>
<td>10^{-1}</td>
<td>Permeable</td>
<td>4 \times 10^{-3}</td>
<td>10 \pm 2</td>
<td>0.04 \pm 0.2</td>
<td>6 \pm 1</td>
</tr>
<tr>
<td>VII</td>
<td>Coarse and uniform sands, fissured limestones and marls</td>
<td>5 \times 10^{-3}</td>
<td>-</td>
<td>2 \times 10^{-2}</td>
<td>2 \pm 1</td>
<td>0.2 \pm 0.4</td>
<td>2 \pm 12</td>
</tr>
</tbody>
</table>

*TABLE IV*

Permeability, filtration velocity and measuring time (for 2" borehole) for various categories of rocks and soils, for different heads (i) and for two decreasing tracer concentrations (C/C_o = 0.1 and C/C_o = 0.01) *
| VIII | Well sorted, coarse sands with addition of gravel, fissured limestones | 1+2.5 | 40+80 | 0.04+0.08 | 1+0.5 | 2+1 | 0.4+0.8 | 6+3 min. | 12+6 min. | - | - | - |
| IX | Fine grained slightly sandy gravels, fissured and coarstic cavernous limestones (Highly permeable) | 2.5+5.0 | 80+160 | 0.08+0.16 | 0.5+0.25 | 1+0.5 | 0.8+1.6 | 3+1.5 min. | 6+3 min. | - | - | - |
| X | Middle or coarse uniform gravels, cavernous limestones with distinct net of unclogged canals | > 5 | > 160 | > 0.16 | < 0.25 | < 0.5 | > 1.6 | < 1.5 min. | < 3 min. | - | - | - |

*) First five columns according to Korshuk (R. Krajewski, Geologiczna Obstuga Kopaliń, W.G. Warsaw).
<table>
<thead>
<tr>
<th>Mineralogic Composition</th>
<th>Conc. Cr(^{51}) ppm</th>
<th>Recovery %</th>
<th>HTO Cr(^{51})-EDTA</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz sand</td>
<td>10(^{-4})</td>
<td>100</td>
<td>90</td>
<td>no measurable delay</td>
</tr>
<tr>
<td></td>
<td>10(^{-3})</td>
<td>100</td>
<td>99</td>
<td>very slight delay of Cr(^{51})-EDTA</td>
</tr>
<tr>
<td></td>
<td>10(^{-2})</td>
<td>100</td>
<td>100</td>
<td>very slight delay of Cr(^{51})-EDTA</td>
</tr>
<tr>
<td>Quartz sand + 10 % quartz powder</td>
<td>10(^{-4})</td>
<td>100</td>
<td>90</td>
<td>no measurable delay</td>
</tr>
<tr>
<td></td>
<td>10(^{-3})</td>
<td>100</td>
<td>98</td>
<td>very slight delay of Cr(^{51})-EDTA</td>
</tr>
<tr>
<td></td>
<td>10(^{-2})</td>
<td>100</td>
<td>99</td>
<td>no measurable delay</td>
</tr>
<tr>
<td>Quartz sand + 10 % calcite powder</td>
<td>10(^{-3})</td>
<td>100</td>
<td>97-98</td>
<td>very slight delay of Cr(^{51})-EDTA</td>
</tr>
<tr>
<td></td>
<td>10(^{-2})</td>
<td>100</td>
<td>92-93</td>
<td>slight delay of Cr(^{51})-EDTA</td>
</tr>
<tr>
<td>Quartz sand + 10 % microcline powder</td>
<td>10(^{-2})</td>
<td>100</td>
<td>93-94</td>
<td>very slight delay of Cr(^{51})-EDTA</td>
</tr>
<tr>
<td>Quartz sand + 10 % albite powder</td>
<td>10(^{-2})</td>
<td>100</td>
<td>97-98</td>
<td>slight delay of Cr(^{51})-EDTA</td>
</tr>
<tr>
<td>Quartz sand + 10 % anorthosite powder</td>
<td>10(^{-2})</td>
<td>100</td>
<td>92-93</td>
<td>slight delay of Cr(^{51})-EDTA</td>
</tr>
<tr>
<td>Quartz sand + 10 % bictite powder</td>
<td>10(^{-2})</td>
<td>100</td>
<td>93-94</td>
<td>very slight delay of Cr(^{51})-EDTA</td>
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<tr>
<td>Quartz sand + 10 % muscovite powder</td>
<td>10(^{-2})</td>
<td>100</td>
<td>100</td>
<td>no delay</td>
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<tr>
<td>Quartz sand + 10 % augite powder</td>
<td>10(^{-2})</td>
<td>100</td>
<td>78</td>
<td>considerable delay of Cr(^{51})-EDTA</td>
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<td></td>
<td>10(^{-1})</td>
<td>100</td>
<td>87</td>
<td>too short test</td>
</tr>
<tr>
<td>Quartz sand + 10 % hornblende powder</td>
<td>10(^{-2})</td>
<td>100</td>
<td>99</td>
<td>considerable delay of Cr(^{51})-EDTA</td>
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<tr>
<td>Quartz sand + 10 % chlorite powder</td>
<td>10(^{-2})</td>
<td>100</td>
<td>68</td>
<td>too short test; HTO max after 17h</td>
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<tr>
<td></td>
<td>10(^{-1})</td>
<td>100</td>
<td>98</td>
<td>very long delay of Cr(^{51})-EDTA max after 50h, HTO max after 17h</td>
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<tr>
<td>Quartz sand + 10 % kaolinite powder</td>
<td>10(^{-1})</td>
<td>100</td>
<td>100</td>
<td>considerable delay of HTO, slight delay of Cr(^{51})-EDTA</td>
</tr>
<tr>
<td>Quartz sand + 10 % illite shale powder</td>
<td>10(^{-1})</td>
<td>100</td>
<td>90</td>
<td>long delay of both Cr(^{51})-EDTA and HTO</td>
</tr>
<tr>
<td>Quartz sand + 10 % bentonite (montmorillonite) powder</td>
<td>10(^{-1})</td>
<td>80</td>
<td>90-100</td>
<td>long delay of HTO</td>
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</table>
Tritium and ($\alpha + \beta$) Activity Variations in a Glacier Profile

**Fig. 1**

Summer Horizon based on pollen stratification

<table>
<thead>
<tr>
<th>Year</th>
<th>Activity (cpm/kg)</th>
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<tbody>
<tr>
<td>1963</td>
<td>100, 200, 300, $\alpha + \beta$ Activity</td>
</tr>
<tr>
<td>1962</td>
<td>904, Tritium</td>
</tr>
<tr>
<td>1961</td>
<td></td>
</tr>
<tr>
<td>1960</td>
<td></td>
</tr>
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<tr>
<td>1953</td>
<td></td>
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<tr>
<td>1952</td>
<td></td>
</tr>
<tr>
<td>1951</td>
<td></td>
</tr>
</tbody>
</table>

Depth (Meters)

Tritium Units
Fig. 2
GEPATSCH DAM - LONGITUDINAL SECTION THROUGH THE AXIS OF THE DAM
VERTICAL FLOW IN THE BOREHOLES
Fig. 3 Ranges covered by various types of probes

- Range covered by Guizerix's probe
- Range covered by normal probe
- Range covered by Matrhofer's probe

$\frac{10000}{C_0 q_1}[\text{min}]$

$V_t[\text{m/h}] 10$

$0.0001$ $0.001$ $0.01$ $0.1$ $1$
Fig. 4
PRINCIPLE OF THE XUELS-FORGE

Fig. 5  VARIATION OF THE WATER CONTENT
Fig. 6 Arrangement to measure density and moisture of an (imitated) underground aquifer from a tube surrounded by a gravel filter (schematic)

$\rho_a$ = Density of the soil or the aquifer including water content (g/cm$^3$)

$\rho_i$ = Density of gravel filter including its water content (g/cm$^3$)

$\varphi_a$ = Moisture of soil or aquifer (% by volume)

$\varphi_i$ = Moisture of gravel filter (% by volume)

$D$ = Thickness of gravel filter

$\varnothing_B$ = Boring diameter

$\varnothing_R$ = Outside diameter of (filter) tube

d = Wall thickness of (filter) tube
Fig. 7 Relating to the measurement of the density $\rho_a$ of the soil from gauge tubes surrounded by a gravel filter with an outside diameter $\phi_B$

Left: Dependence of the normalized counting rate on $\phi_B$ with the parameter $\rho_a$

Right: Normalized calibration curves for the measurement of $\rho_a$ with the parameter $\phi_B$

Iron tube: $\phi_B = 60$ mm, $d = 3.3$ mm
Density of gravel filter $\rho_i = 1.9$ g/cm$^3$

Probe A: $n_o = 3400$ cps; Probe B: $n_o = 1600$ cps
Fig. 8 Normalized moisture calibration curves for different separations neutron source-detector (the probe is located directly in the soil) $n_0 = 10^4$ cpm employing a 10-mc Ra-Be neutron source.

Fig. 9 Moisture calibration curves for various thicknesses $D$ of the gravel filter:
- Moisture of gravel filter = 37 %
- Iron tube $\beta = 50$ mm (water-filled)
Map of the Area Studied

Fig. 10

Fig. 11.1 Tritium Concentrations and the Log of the Well

Fig. 12.1 Groundwater Levels, Precipitation, Evapotranspiration and the Tritium Concentrations in the Precipitation.
**Fig. 13** Box- or "plate"-model for downward movement of soil moisture. The soil is divided into layers (boxes, plates), the thickness of which is the travel path (=height equivalent of theoretical plate - HETP) over which the exchange equilibrium between draining and stationary water is almost completed. The volumes of the two phases in this example are assumed as 1:4. The figures on the right-hand side show how the tracer concentration \( c_0 \) in the draining water penetrating from above decreases during passage if the soil moisture at field capacity originally contained no tracer. The concentration decrease is very steep if HETP is small.

**Fig. 14** (to be read in conjunction with Table 1). Loamy soil without vegetation, labeled 9 July 1964. F (heavy line), soil moisture (volume percentage); \( q \) (boundary of hatched area); amount of tracer per 10-cm layer of soil, as a percentage of the amount of tracer originally deposited in the soil; a to e, samplings 4, 26, 82, 132 and 214 days after labeling, respectively.
Fig. 15
Yearly variation of rainfall—(P) and groundwater recharge—(Q)

Fig. 16
Nahal Oren catchment area
Rainfall- Recharge relations
Fig. 17— PUMPING FROM A TWO-LAYERED AQUIFER
LEGEND

- MEDIUM SIZE GRAIN SAND
- CALCAREOUS SANDSTONE WITH SAND
- COARSE SAND WITH SOFT-BEDDED CALC SANDSTONE
- GREY SAND WITH SHALE FRAGMENTS
- GREY SAND WITH SMALL MUDDY BLACK GRAVEL
- BLACK CLAY

Fig. 18 - GEOHYDROLOGICAL CROSS-SECTION OF EXPERIMENTAL SITE
Fig. 19 - PUMPED WATER BREAKTHROUGH CURVES OF TESTS "A" AND "B"
Fig. 20  BREAKTHROUGH CURVES AT OBSERVATION WELLS 15 AND 15A
The Model of Groundwater-Recharge Conditions

Fig. 21

Fig. 22 Profile through W Schiermonnikoog

Fig. 23 Variation of Age with Depth
Fig. 24 Representation of Function

\[ \delta^13C = \delta^2H \times q \times \frac{[\text{HCO}_3^-]}{[\text{CO}_2^+] + [\text{HCO}_3^-]} \]

- o water samples in disintegrated rocks
- o water samples in solid rocks
- o water hardness < 2mM HCO$_3$-/l

Fig. 25 $^1^4$C OF WATER SAMPLES IN DEPENDENCE ON THE DEPTH OF EXTRACTION (DISINTIGRATED ROCKS)

- + corrected values
- * uncorrected values