# MEASUREMENT OF FLOW AND DIRECTION OF GROUND WATER BY RADIOACTIVE TRACERS: HYDROLOGICAL EVALUATION OF A WASTE DISPOSAL SITE AT "INSTITUTO DE PESQUISAS ENERGÉTICAS E NUCLEARES (IPEN)"

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CENTRO DE APLICAÇÕES DE RADIOISÓTOPOS E DE RADIAÇÕES NA ENGENHARIA
E NA INDÚSTRIA – CARREI
ÁREA DE APLICAÇÕES NA PRESERVAÇÃO E APROVEITAMENTO DE RECURSOS NATURAIS

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CARREI-AAPARN

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# MEASUREMENT OF FLOW AND DIRECTION OF GROUND WATER BY RADIOACTIVE TRACERS: HYDROLOGICAL EVALUATION OF A WASTE DISPOSAL SITE AT "INSTITUTO DE FESQUISAS ENERGÊTICAS E NUCLEARES (IPEN)"

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## ABSTRACT

~~This report~~ is describe~~s~~d the method of determining flow and direction of ground water by using radioactive tracers in ground water borings. Various parameters controlling the measurements are discussed in detail. Application of the method in studying a variety of geohydrological problems ~~has been~~ is indicated. Comparison of the method with conventional pumping tests ~~has been~~ are made. [illegible] of the hydro[illegible] [illegible] disposal site at IPEN

The first application of the borehole dilution technique by Centro de Aplicações de Radioisotopos e Radiações na Engenharia e na Industria (CARREI) was made to study the movement of ground water around the radioactive waste disposal site at Instituto de Pesquisas Energéticas e Nucleares (IPEN). A study of geohydrological evaluation of the disposal site has been made. Field experiments in the nearest available monitoring well 850 m downstream were made to determine flow and direction of ground water movement. $^{131}$I and $^{82}$Br were used as radioactive tracers for flow measurements, while $^{51}CrCl_3$ was used as an absorbing type tracer for determining direction of flow. The field equipment used consisted of gramma scintillation probes, scaler count rate meter, isotope injection assembly and extension rods. Natural gamma log of the well was taken to verify the construction of the borehole and to have an idea of geological stratification at the site. Estimates of velocity of ground water at the waste disposal site were made and therefrom travel times of radioactive nuclides relative to local ground water were computed.

The average filtration velocity at 850 m downstream of the waste disposal site has been found to be 3.66 cm/d. The local direction of ground water is towards old Jaguare stream.

Based on the estimates of bulk density 1.8 g/cm$^3$, porosity 35%, distribution coefficient 1000 for $^{137}C_s$ and 30 for $^{90}$Sr, following analysis regarding the radioactive waste disposal site at IPEN has been made:

Filtration rate of ground water = 6.48 cm/d

Stage speed of ground water = 18.5 cm/d

Arrival time of ground water upto nearest point of old Jaguare canal = 2431 d

$$\frac{\text{Velocity of radionuclide}(^{137}\text{Cs})}{\text{Velocity of ground water}} = 1.94 \times 10^{-3}$$

$$\frac{\text{Velocity of radionuclide}(^{90}\text{Sr})}{\text{Velocity of ground water}} = 6.44 \times 10^{-3}$$

The values of field permeability determined are as following:

determined by radiotracer technique = 3.28 x 10$^{-3}$ cm/s

determined by pumping tests = 8.60 x 10$^{-4}$ cm/s

## 1 – INTRODUCTION

Radioactive isotopes are normally used as tracers to determine local hydrological characteristics, viz., direction and speed of ground water flow; stratification of aquifer, its porosity and transmissivity. The radioactive tracers are used in ground water investigations via the single(16) and multiwell methods(1). In single well method, the velocity and direction of ground water flow are generally ascertained from a single borehole drilled in the area of investigation.

The present report reviews the technique of single well method and reports some of the investigations carried out for hydrological evaluation of a radioactive waste disposal site at IPEN.

## 2 – DETERMINATION OF VELOCITY OF GROUND WATER

One of the important parameter in ground water investigations which needs to be determined is the filtration velocity, $v_f$, as defined by Darcy's law;

$$v_f = k_3 \ . \ I \tag{1}$$

where $k_3$ is the permeability of the aquifer and I is the gradient head of the ground water flow. Filtration velocity $v_f$ can also be measured from the stage speed V between two boreholes and effective porosity in pumped or unpumped aquifer i.e.,

$$v_f = n \ . \ V \tag{2}$$

### 2.1 – Principle of the Single Well Method

A direct means of determining filtration velocity is the dilution method. In this method, the water in a borehole is labelled with a tracer solution, and the dilution of the labelled water by inflowing ground water is measured. The dilution rate of the tracer, which is homogeneously distributed in a volume V in the borehole, is described by a differential equation, the solution of which renders the relationship:

$$v_a = - \frac{V}{F\,t} \ln c/Co \tag{3}$$

where

$v_a$ = apparent velocity;

V = measuring volume (the volume in which dilution takes place);

F = area of cross section of the measuring volume perpendicular to the direction of flow;

t = time interval between measurement of concentration Co and c.

The horizontal flow pattern in the aquifer is distorted owing to the presence of a borehole and different flows there in. Thus, the measured velocity in the borehole ($v_a$) is related to the actual filtration velocity ($v_f$) by additional flow terms, which account for the distortion of the natural flow field.

Thus:

$$v_a = \alpha . v_f + v_c + v_v + v_m + v_d \qquad (4)$$

where,

$v_c$ = apparent filtration velocity caused by density effects (concentration, temperature, etc.);

$v_v$ = apparent filtration velocity caused by vertical currents;

$v_m$ = apparent filtration velocity caused by artificial mixing;

$v_d$ = apparent filtration velocity caused by molecular diffusion of the tracer.

The correction factor $\alpha$ which accounts for the distortion of the flow lines owing to the presence of the borehole, is defined by

$$\alpha = Q_a / Q_b \qquad (5)$$

where $Q_a$ is the horizontal flow rate in the borehole and $Q_b$ is the flow rate in the same cross section of the formation (i.e. in the absence of the borehole).

In the absence of all other flows but horizontal:

$$v_f = - \frac{V}{\alpha F t} \ln c/Co \qquad (5a)$$

$$v_f = - \frac{\pi r_1}{2 \alpha t} \ln c/Co \qquad (5b)$$

### 2.2 – Borehole Construction and Calculation of α

Normal construction of a borehole consists of a perforated filter tube surrounded by a gravel pack. If the borehole of radius $r_3$ has a filter of external and internal radius $r_2$ & $r_1$ and if the respective permeabilities of the filter tube, gravel pack and the formation are $k_1$, $k_2$ and $k_3$ (Figure 1), then, application of the potential theory to this borehole, gives the following expression for $\alpha$:(18,28)

$$\alpha = \frac{8}{(1 + k_3/k_2)\ \{1 + (r_1/r_2)^2 + k_2/k_1\ [\ 1 - (r_1/r_2)^2\ ]\} + (1 - k_3/k_2)\ \{(r_1/r_3)^2 + (r_2/r_3)^2 + k_2/k_1\ [\ (r_1/r_3)^2 - (r_2/r_3)^2\ ]\}} \qquad (6)$$

In the absence of a gravel pack, $r_2 = r_1$ and $k_2 = k_3$, and the equation (6) is reduced to Ogilvi's formula(38).

$$\alpha = \frac{4}{1 + (r_1/r_2)^2 + k_3/k_1 \left[ 1 - (r_1/r_2)^2 \right]} \qquad (7)$$

### 2.3 – Filter Tube Permeability

Various designs of the filter tubes which can be recommended for installations are shown in Figure 2. The permeability of the filter tube $k_1$ can be measured from experimental as well as theoretical model test(29). Model experiments with various types of filter tubes have revealed(10) that the value of $k_1$ was independent of the type of filter used, the thickness of the filter tube and $k_2$, $r_3$, $k_3$. In most of the cases, 10% perforations in the filter tube are sufficient even for permeable materials(4). However, for highly permeable, coarse gravels, perforations to the extent of 20 – 30% are recommended.

### 2.4 – Permeability of the Gravel Pack and Aquifer

According to the equation (6) and (7), the permeabilities of the aquifer, $k_3$, and of the filter gravel, $k_2$, must be know for a calculation of $\alpha$ – value. On the other hand, it is often precisely the $k_3$-value that is to be determined with the aid of filtration velocity. To examine this basic question of applicability of the method, $\alpha$ was calculated by equation (6) as a function of the parameters $k_2/k_1$ and $k_3/k_2$. (Figures 3 - 7) show the results of computer calculations(16,10) made from Equation 6. The conclusion drawn from these studies is that $\alpha$ remains independent of the parameters $k_2/k_1$ and $k_3/k_2$ and depends only on the radii $r_1$, $r_2$ and $r_3$, and hence can be calculated with sufficient accuracy (10%), if the conditions,

$$k_1 \geqslant k_2 \geqslant 10 \, . \, k_3 \qquad (8)$$

are fulfilled.

In practice, it is revealed that the condition $10 \, . \, k_3 \leqslant k_2$ is satisfied in most of the cases. If the condition $k_1 \geqslant k_2$ is not satisfied, $\alpha$ must be calculated from the values of $k_1$ and $k_2$ by Equation 6. For this purpose, the permeabilities $k_1$ and $k_2$ will have to be determined by laboratory tests or taken from the available literature(29). The permeabilities $k_1$ and $k_2$ should ensure a sand free entry of the ground water into the filter tube i.e., the grain size of the gravel filter must be large than the perforations of the filter tube. Further, the filter gravel should be so selected that the gravel filter will retain the sand-gravel mixture of the ground water duct, but at the same time allow a desanding of the well. These perequisites are mostly met for example by German Industrial Standards and empirical data adopted in well sinking(3). It is advisable to clean the borehole before experiments, to remove material accumulated in the filter tube.

For the case of the borehole without gravel filter Figure 8 and 9 derived from equation (7), show that $\alpha$ is independent of $k_3$ for $k_1 >> 10 \, k_3$. In the event that $k_1 = k_3$ (i.e. the worst case), a maximum deviation of 20% for $\alpha$ must be taken into account. This is admissible seeing the range of accuracy required in practice.

## 2.5 — Effect of Tracer Diffusion

Equation (4) shows that the diffusion of the tracer plays a part in determining dilution rate $v_a$. A tracer concentration may eliminate density effects but does not eliminate diffusion of the tracer. Even in the absence of all other interfering parameters, diffusion always exists, but its influence diminishes as $v_f$ increases. Matvejev$^{(35)}$ showed that the diffusion velocity $v_d$ may be estimated from the relationship

$$v_d = \frac{\pi D}{r_i} \simeq 10^{-5} \text{ cm/s} \simeq 0.01 \text{ m/d}$$

where; D: diffusion coefficiente of the tracer and $r_i$ : inner radius of the filter tube.

Laboratory model experiments$^{(18)}$ have shown that diffusion effects do not become significant for $v_f > 0.3$ m/d, whereas for $v_f < 0.3$ m/d a correction may be applied according to the relation:

$$v_f = \frac{v_a - v_d}{\alpha} \tag{9}$$

provided there are not other disturbing parameters (i.e., $v_c$, $v_v$, $v_m$ are negligible). Without a correction for diffusion, the ratio of the dilution velocity to filtration velocity, in the range of $v_f < 0.3$ m/d, tends to grow rapidly with decreasing filtration velocity. Model experiments$^{(10)}$ have shown that $v_d$, for $v_f = 0$, is about 3 to 4 times greater than the one calculated on the basis of equation (9); therefore, for field tests $v_d = 3\pi D/r_i$ may be taken as an approximation. The variation of diffusion coefficient with tracer concentration$^{(13)}$ is shown in Figure 10 for ready reference.

## 2.6 — Effect of Probe Dimensions

A correction in the dilution volume in the equation (5) due to the volume of the detector probe, has been suggested by various workers$^{(27,32)}$. If the detector probe has a radius $r_o$, then equation (5.b) becomes:

$$v_f = -\frac{\pi\,(r_i^2 - r_o^2)}{2\alpha r_i\, t} \ln c/Co \tag{10}$$

Experiments have shown that α - value remains independent of $r_o/r_i$ within the range of $0 \leq r_o/r_i \leq 0.92$. When the diameter of the probe is large relative to borehole diameter, the measurement time is reduced but the flow may be distorted. Large diameter probes are apt to be more influenced by tracer absorption on the walls and by the tracer outside the measuring volume. It is preferable to use a probe whose diameter does not exceed half of the filter tube diameter.

## 2.7 — Effect of Mixing

The derivation of the equations (3), (5) and (10) is based on the assumption that the distribution of the tracer throughout the measuring volume is uniform at all the times. In case of incomplete mixing of the tracer in the dilution volume, no unambiguous exponential dilution results but rather two semi-logarthmic straight lines of different slopes are often encountered. Only with filtration velocities less than 0.3 m/d does the molecular diffusion of the tracer suffice to distribute the tracer homogeneously throughout the dilution volume. In many cases a concentration gradient is produced through a displacement of the labelled water column by the detector centred in the measuring volume. As a rule, the initial part of the dilution curve obtained can be discarded for calculation purpose, because of incomplete mixing or residual currents.

Therefore, it is necessary, in general, to provide for an artificial mixing of the tracer in the dilution volume by a mixing device. The mixing device generally consists of a wire coil moved up and down. Unique $v_f$ value can be attained only above a minimum mixing rate. This mixing rate depends on the filtration velocity and on the $\alpha$ – value. Too intense mixing, may, especially if very samall velocities are involved, lead to additional disturbance of the flow field or forcing the tracer out of the measuring volume.

### 2.8 – Effects of the Vertical Flow in Filter Tube

Vertical flow may result in the measuring volume when the ground water flow lines are not perpendicular to the borehole(31) or when the borehole penetrates stratified water bearing formations. This vertical flow consequently increases the dilution velocity and a correction must be allowed for calculating $v_f$. This correction in practice is not possible because it is not readily possible to determine the vertical flows. However, it is possible, through technical measures, to minimize the vertical flow such that they do not disturb the measurement results. To eliminate vertical flow within the filter tube, use of packers to seal the top and bottom of the dilution volume has been suggested by various workers(16,27,15). Model and field experiments have proved that even the seals do not fully prevent the influence of vertical movement of the water. The water bypasses the seals through the gravel pack, enters the measuring volume and disturbs the measurements. Perhaps in uncased borehole in hard rocks, it could be possible to stop vertical flow by using seals.

Seals should increase the resistance for vertical currents such that the horizontal flow $Q_h$ through the dilution volume substantially outweighs the vertical throughflow $Q_v$ ($Q_h >> Q_v$). Figure 11 shows a filtration velocity measuring system used by Institut fur Radiohydrometrie. Above and below the measuring volume is a seal in which detectors are fitted to monitor possible vertical flow immediately outside the filter tube(9). If ground water retains its original direction of flow after passing the measuring volume, the filtration velocity can be determined by the equation (5). If, on other hand, the flow is diverted from its original direction into a vertical flow, as show in Figure 11, then according to equation (4), the dilution velocity is

$$V_a = \alpha V_f + V_v$$

or

$$Q_a = Q_h + Q_v$$

where $Q_a$ is the total ground water discharge in the measuring volume as determined from equation (3). If the vertical discharge $Q_v$ is approximately determined from the relation,

$$Q_v \simeq \frac{L\pi(r_3^2 - r_2^2)\,n}{t}$$

where L is the mean distance of the measuring volume from the detectors (Figure 11), t is time of flow over the distance L, $r_3$ is radius of the borehole, $r_2$ is external radius of the filter tube and n is porosity of the gravel pack.

By determining the difference $Q_a - Q_v$, the horizontal flow and hence the filtration volocity can be determined by equation (5.b).

In the presence of the vertical flow, the dilution method can be used for determination of the filtration velocity only when the horizontal discharge is considerably greater than the vertical discharge in the filter tube.

Since the cross-section for the vertical flow is usually much smaller than the horizontal one, vertical velocity may be of the same order of magnitude as the horizontal velocity, $v_f$, without significantly interfering with the measurement of $v_f$ (7). Since the flow resistance is basically controlled by permeability and the length of gravel pack through which water flows around the seal, the length of the seal certainly will influence its effectiveness. Long seals compared to the length of the dilution volume may cause a disturbance of the two-dimensional flow field and thereby increase the $\alpha$ - value. Model and field tests have shown (10) that with seals of length 10 and 25 cm and a length of 25 cm of the dilution volume, the increase of $\alpha$ - value amounted to about 10%.

With measuring devices provided with seals, filtration velocity in a borehole can be measured at various depths. Measurements at several depths can thus take considerable time. In earlier measurements of filtration velocities by dilution method, the entire water column of the filter tube was tagged with radioactive tracer and the decrease in its concentration was then measured as a function of depth (37). This way, the time required for logging the filter tube is reduced, but the interpretation of results is often distorted by the exitence of the vertical flows. To correct this, separate injections of tracer can be made to determine upward or downward vertical currents. From the vertical flow path and flow time of tracer in the filter tube, vertical flow velocity and hence vertical discharge can be determined. Substraction of vertical discharge from total discharge obtained from equation (5.a), yields the horizontal filtration velocity. With this method, however, not all measurement conditions for $v_f$ determination can be fulfilled; as a check, therefore, it is necessary to carry measurements with seals at a few points.

The decrease in concentration of the tracer solution (i.e., the counts of detector) can be recorded at surface in digital or analog form, so that they can be fed into a computer if possible. If no computer is available, it is advisable to plot the concentration decrease semilogarithically against time. The slope of the line is proportional to the filtration velocity.

## 2.9 – Velocity Range, Error Involved, Cost and Validity Conditions

The lower limit of measurable velocity by dilution method lies in the range of diffusion velocity i.e. about 1 cm/d. Upper limit of measurable velocity is turbulent flow for which theory for estimation of $\alpha$ has not been developed. Practical upper limits depend upon instrumentation and technique (i.e., response, mixing, recording ability, etc.). Field experiments have reported velocities upto 120 m/d under pumping conditions and 10-20 m/d under natural gradients.

Error in the value of $v_f$ is determined basically by the uncertainty involved in the $\alpha$ - value. A careful construction of the borehole with right choice of filter tube and the surrounding gravel pack is essential condition for accurate application of the dilution method. Experience shows that in most instances there is lack of dependable supporting site information and thus it becomes difficult to ascertain the results of the dilution method. Model experiments show that uncertainty in permeability value of the filter tube and gravel pack leads to an error in $\alpha$ and $v_f$ of about 10% if equation (8) is fulfilled. Under unfavorable field conditions, the dilution method can be expected to give about 50% accuracy for absolute values of filtration velocity.

$v_f$ measurements can be carried out by a trained person who has professional experience of hydrological problems, measurement technique and radiation protection. The cost of a single $v_f$ measurement is made up of personnel, travelling, transport and equipent costs. Further, the cost depends on the number of the wells in the ground water field and the number of measurements required.

Borehole dilution method is best suited to homogeneous formations like alluvial gravel and sands. In the presence of significant vertical flows or in fractured and karstic rocks the results of dilution methods are utilizable normally only qualitatively. Even qualitative measurements are of immense practical importance in investigations of ground water.

The results of dilution method in a borehole in principle can be extrapolated to surrounding aquifer. This extrapolation is valid in all cases where there is horizontal flow all along the depth. If the aquifer is composed of broken or dislocated layers, the net work of borehole must be closer to gather reliable data applying to the entire ground water field.

Certain advantages of the borehole dilution method can be listed as following:

- the investigation can be carried out in unpumped ground water and therefore give the flow rate of the unstressed aquifer;
- if proper well construction is executed, detailed information on the stratification of the aquifer can be obtained;
- the measurement can be performed in boreholes of any diameter (>1.5");
- it is economical to determine ground water velocity by the method.

## 2.10 – Comparison of Dilution Method with Pumping Tests

Using the dilution method one can determine the filtration velocity (i.e., Darcy velocity) and if gradient is known, the permeability of the aquifer $k_3$ can be determined. The traditional methods of determining the $k_3$ value are pumping tests and in-situ packer tests. It is interesting therefore to compare the dilution method and the conventional pumping tests for ascertaining the extent to which these methods confirm and complement each other. Following points are worth mentioning while a relative comparison of the methods is attempted.

2.10.1 – The calculation of $k_3$, based on Darcy's law in all cases require that the ground water gradient head I at the test site be known. The determination of I from the ground water levels in gauges, which appear simple in principle, can become problematic if, observation net work is not close enough; the ground water is stressed, gauges are at different pressures or if foundations of structures penetrate the ground water zone.

2.10.2 – The zone of influence in the aquifer for which the $k_3$ values are derived by dilution method and the conventional pumping methods, differ considerably. Vertically, the dilution method can log each individual strata. The packer tests furnish an average $k_3$ value around the bottom of the borehole whereas pumping tests yield a $k_3$ value which applies to the entire thickness of the aquifer tapped by the boring. Horizontally, the zone of influence for the various methods in relation to the filter tube diameter, $2r_1$, can be approximately expressed as:

$\alpha \cdot 2r_1$ for dilution method;

$10r_1$ for packer tests;

$10 - 10^3\ r_1$ for pumping tests (depending upon type of measurement).

In dilution method stream line density of ground water is measured in the horizontal plane whereas in pumping tests both horizontal and vertical planes are involved.

It can be said that $k_3$ - values determined by dilution method and packer tests are more readily comparable. In comparasion of dilution method and large area pumping tests, agreement will be obtained only if the measuring points of the dilution method are representative of the entire ground water duct. In general, however, maximum $k_3$ - values obtained by dilution method can be expected to be higher than $k_3$ - value furnished by pumping test, since thin layers of lesser permeability do not effect the dilution method due to the presence of gravel pack:

2.10.3 – Water levels, discharges and other field conditions which normally change with time, should be comparable while the results of various methods are analysed. It may often occour that measurement results of a pumping test, dating far back and conducted under other or unknown conditions, are the only ones which are avialable for comparison purposes.

In short, it can be summarized that undisputable comparisons between different methods to determine $k_3$ - value are possible only under favorable field conditions.

Systematic determinations of $k_3$ - value, first by packer tests and then by dilution method, were carried out in Germany in the past. Packer tests were conducted by installing filter nozzle at various bottom depths during sinking of a well. The $k_3$ - value was ascertained by small scale pumping experiment under hydrostatic or dynamic method(33). Altogether, 38 measurements were carried out in the alluvial coarse gravels. The agreement between the pair of measured values was up to 85%(8).

Gaspar et al.(14) carried out measurements in sands and gravels, and the results of dilution method agreed well with those obtained from pumping experiments Similar comparative measurements were reported by Milde(36), Kratzschmar(30), Drost et al.(10) and IfR(18,19,21) and in all the cases the data obtained for coarse gravels gave satisfactory results.

In the light of this, it can be said that the dilution method can provide substantially the same results as the usually very onerous pumping experiments.

## 3 – DETERMINATION OF DIRECTION OF FLOW OF GROUND WATER

To find the direction of flow of ground water in a well, the water column in the well is labelled with a radiotracer solution and allowed to flow away in the aquifer. The radial distribution of the tracer in labelled segment is then measured by means of a directionally sensitive detector as shown in Figure 12. The direction of maximum activity of tracer corresponds to the direction of flow. A better determination of flow direction is achieved if the tracer is adsorbed in and around the borehole.

To make the detector directionally sensitive, it is collimated by a slotted lead shield. The collimated window can be rotated continuously by means of a drive motor in the probe(20).

The probe is lowered down in the borehole by stiff square-section metal rods of suitable lenghts. Orientation of the collimated window can also be indicated by a gyroscope attached to square rods above ground while rotating the probe mechanically.

Point injection in the centre of the filter tube provides the best direction diagram. Vertical currents may carry the tracer in directions not compatible with the direction of flow in the segment of the aquifer being tested. Measurement by this method furnishes direction that is true only for the surrounding of the borehole. If it is assumed that the ground water flow lines are not assymetrically distorted by inhomogeneities of the formation or stresses, the results may be considered as representing the general direction of flow.

In most of the measurements carried out in the past, the difference between the measured and actual direction was less than 3°. The reproducibility of the method in the field is better than 10%.

## 4 – SELECTION OF TRACERS FOR DETERMINATION OF FLOW AND DIRECTION OF GROUND WATER

For determination of velocity of ground water use is made of gamma emitting radionuclides that have a half-life appropriate to the duration of the experiment and are only sparingly adsorbed on the probe, filter tube, gravel and the aquifer. In practice, to date, bromine-82 (as $NH_4Br$ solution) and iodine-131 (as NaI solution) have proved particularly suitable. For reduction of adsorption, the radionuclide is prepared with certain amount of carrier. It is advisable to add sodium thiosulphate in the tracer solution, to avoid escape of free bromine or iodine. It is recommended that the concentration of carrier etc. be kept as low as possible ($< 10^{-4}$ moles/l for $NH_4Br$).

For determination of direction of ground water flow, a radionuclide of gamma energy range of 0.4 – 0.7 Mev may be used. Bromine-82 and iodine-131 were used in early studies, but now the adsorbing type tracers like gold-198 (as $AuCl_3$ solution)(13) and chromium-51 (as $CrCl_3$)(40) are preferably used. Amount of radioactive tracer to be used depends upon the experimental conditions viz., filter tube dimensions, flow rate, detector sensitivity. These parameters need to be ascertained by previous calibration and experience.

## 5 – APPLICATION OF DILUTION METHOD IN HYDROGEOLOGICAL INVESTIGATIONS

Determination of filtration velocity (consequently permeability) and direction of ground water flow by radiotracer techniques have been applied in solving variety of problems. Some examples are given below:

- ground water exploitation(34,5);
- well installation(10);
- seepage from dams, reservoirs, rivers, canals(11,22,26);
- soil consolidation, and load on ground water(2);
- sanitary engineering, waste disposal and pollution(6);
- engineering geology(18,8,19,20,21,23,12).

## 6 – RADIOACTIVE WASTE DISPOSAL SITE AT IPEN

The radioactive waste disposal site at Instituto de Pesquisas Energéticas e Nucleares is situated in the western part of the Institute and lies in the slope of the little hill of Cidade Universitária. Figure 13 shows the location of the disposal site with respect to old Jaguaré stream and Pinheiros river, which are about 450 m and 1600 m away from the disposal site. Jaguaré stream, from its intersection with Avenida Corifeu de Azevedo Marques and upto discharge outlet into Pinheiros river (Figure 13) is now a closed channel. The channel now collects monsoon run-off and local effluents from upstream side of the intersection with the Avenida Corifeu. Figure 14 shows the topographic details of the waste disposal site. The contours vary from 750 m to 735 m and are sloping in the north-west direction towards the course of old Jaguaré stream. An areal photograph of the site is shown in Figure 15.

The waste disposal site is characterized by good soil cover of low permeability and deep water table. The site is devoid of significant vegetation and suffers erosion after heavy spell of rain. Average annual rainfall in the area is about 1300 mm. Levelling of the area of construction of trenches and planning of drains to avoid further erosion is underway.

### 6.1 — Sub-Surface Geology

Based on the records of various wells drilled in the past in the region of Jaguaré, Cidade Universitária and Butantã, the sub-surface geology of the area can be generalized as following(39):

- quarternary alluvial sediments with clay: thickness of this layer is variable within 10 meters;
- tertiary fluvial sediments of São Paulo Basin, thickness of which varies from 40 to 150 meters — the thickness decreases in the westernly direction;
- pre-cambrian crystalline basement with occurrence of cracks and fissures between 70 to 120 and 250 meters;
- the water table aquifer containing the rainfall infiltration consists of the first 10 to 15 meters of the sediments.

### 6.2 — Monitoring Well in the Vicinity of the Disposal Site

Monitoring wells at the disposal site are planned to be installed in a grid pattern to establish local ground water table and to continue hydrological evaluation of the waste disposal programme of the Institute. At the moment one 4" diameter well and some piezometers are existing at about 850 m away from the disposal site in the north direction. The well and the piezometers are located in the complex of Instituto de Pesquisas Tecnológicas (IPT). The location of the main well with respect to the piezometers is shown in Figure 16(37). The main well is of 4" diameter while the diameters of the piezometers are 1.5". The well penetrates a depth of 12 m of the local aquifer. Its filter tube is perforated from 5.5 m to 11.5 m and is provided with graded gravel pack.

The piezometers are penetrating upto different i.e., shallow, medium and bottom depths of the local aquifer. The perforations in the piezometers are provided only in their bottom portion of one meter. The details of construction of the central well and various piezometers and local geology are shown in Figure 17(24). The geological section of strata along piezometers 10-8-5-2 is shown in Figure 18(24). The water table in the central well was found to be 3.25 m below ground. The local area is rather plane and the difference in topographical levels between this area and waste disposal site of IPEN is about 25 m(25). In fact, the well and the piezometers are the only monitoring facilities which are nearest to the diposal site in the downstream direction and thus were chosen for first series of determination of filtration velocity and direction of local ground water. Later, when additional boreholes are drilled as planned, more information in the vicinity of the disposal site would become available.

## 7 — FIELD INVESTIGATIONS

### 7.1 — Determination of Natural Gamma log of the Borehole

For verifying the construction of the borehole, natural gamma logging of the borehole was carried out. The log was obtained by a NaI(Tl)gamma scintillation probe while observing its response at every 25 cm depth interval. The log thus obtained is shown in Figure 17.

### 7.2 — Determination of Filtration Velocity

Both iodine-131 and bromine-82 were used, one by one, as tracers for determination of filtration velocity in the central well. The tracer was injected in the entire water column of the borehole by the injection assembly shown in Figure 19 a. Uniform mixing of the tracer was ensured by moving the dead weight of the injection assembly. The total amount of activity injected in the borehole was 37.65 $\mu$Ci in case of iodine-131 and 27.72 $\mu$Ci in case of bromine-82. These amounts of activities when diluted in the entire volume of the well, yielded around 80,000 cpm by the gamma scintillation probe used for the experiments. The amount of the tracer to be injected was estimated from laboratory calibration experiments. Incidentally, the initial activity in the well, in case of iodine-131, was more than its maximum permissible concentration in drinking water, but the short half life of the tracer (8.3 d) and absence of ground water use in the vicinity, satisfied the health physics aspects of the experiment.

To minimise the loss of tracer due to adsorption, adequate amount of carriers NaI (0.1 g/l) and NaBr (0.5 g/l) were injected into the well prior to the injection of tracer.

Measurement of dilution rate was carried out at 8.5 m depth i.e., at the middle of the perforated filter (see Figure 19 b). The details of the construction of the borehole i.e., radii of the filter tube, gravel pack from which the value of $\alpha$ is to be determined, are shown in Figure 19 c. The values of permeability of the filter tube $k_1$, gravel $k_2$ and of the formation $k_3$, have been reported to be as following(24):

$k_1 = 0.5$ cm/s

$k_2 = 0.5$ cm/s

$k_3 = 8.5 \times 10^{-4}$ cm/s

The value of $\alpha$ calculated by means of equation (7) from the available data of $r_1$, $r_2$, $r_3$, $k_1$, $k_2$ and $k_3$ is 2.94. Graphically the value of $\alpha$ calculated from Figure 4 and Figure 7 ($r_1/r_2 = 0.9$; $r_2/r_3 = 0.7$; $k_2/k_1 = 1$; $k_3/k_2 = 1.7 \times 10^{-3}$) lies in the range of 2.5 to 2.9. Normally, when the condition $k_1 \geqslant k_2 \geqslant 10\ k_3$ is satisfied, $\alpha$ can be computed from the data of $r_1$, $r_2$ and $r_3$. Since the data of radii of the borehole is more reliable than the values of $k_1$, $k_2$ and $k_3$ determined under laboratory conditions, the values of $\alpha$ equal to 2.5 and 2.9 computed graphically from Figure 4 and Figure 7 may be taken as more represetative. An average value of 2.7 has therefore been chosen for the present investigations.

The monitoring of the dilution of radioactivity was carried out by a NaI(Tl) gamma scintillation probe 3.8 cm in diameter and 45 cm long. The dilution rate which seemed to be very slow was monitored for about two hours. The typical dilution curves obtained with iodine-131 and bromine-82 are shown in Figure 20 and Figure 21, respectively. The dilution curves have been obtained after applying the correction regarding the decay of the isotope and the normal background of the monitoring probe. The filtration velocity without applying corrections due to effects of tracer diffusion and probe volume was found to be 4.61 cm/d and 4.65 cm/d and is indicated in the repective figures.

### 7.3 – Determination of Direction of Ground Water

For determining direction of flow, $^{51}$Cr as chromium chloride was used as adsorbable tracer. 1 ml of 1 mCi/ml solution of the tracer was injected at 8.5 m depth. 1 ml of the tracer was taken in 3 mm dia, polyethylene tube by a micro metering pump. The tube was lowered up to the point of injection along with a centering device which was supported by a nylon rope. The pump was operated at a very slow speed and the tracer solution was pushed out from the polyethylene tube. The injection assembly was left in the well till next day so as to allow undisturbed flow and adsorption of the tracer. After 24 hours a collimated gamma scintillation counter was lowered to the point of measurement by means of square section aluminium rods. A gyroscope assembly fitted on top of the borehole was used to indicate the direction of the collimation. The probe was rotated clockwise in steps of 45° and a profile of the radioactivity adsorbed around was obtained by recording the counts at each orientation. The measurement was repeated by rotating the probe in anticlockwise direction. Average of the counts at each orientation was taken and a radial distribution of the tracer activity as shown in Figure 22 was obtained. The resultant direction of the flow of ground water was 47° anticlockwise from the line joining the well and piezometer nº 11. This direction of flow was towards nearby building of the IPT and was in agreement with the general direction of flow as reported in an earlier investigation(25).

### 7.4 – Determination of More Permeable Layers

The determination of more permeable layers penetrated by the borehole was carried out by measuring filtration velocity at various depths along the perforated section of the filter tube of the borehole. For this, entire water column of the borehole was traced by bromine-82 as before. Total amount of the activity used was 25.4 $\mu$Ci.

The gamma scintillation probe was lowered at various depths and its response was recorded at various intervals of time. Care was taken to move the probe up or down very slowly so as to create minimum disturbance of the flow within the borehole.

The filtration velocities (calculated with $\alpha = 2.7$ and without corrections due to effects of diffusion) at upper, middle and bottom portion of the filter were found to be 6.48 cm/d, 2.98 cm/d and 1.53 cm/d repectively.

## 8 – DISCUSSION OF RESULTS

The area where the well and the piezometers are installed appears to be reclaimed area and the shallow sub-surface layers are not which might be existing naturally. Layers of varying permeability and thickness are existing which are causing slightly differing water heads. Ground water level gradient in the area is very small.

The natural gamma log (Figure 17) tallies well with the borehole construction details. The bentonite layer can be identified by higher gamma activity. The layer seems to have compacted itself a little. The natural gamma response after 4 meters is more or less uniform except for a depth interval of 8.0 – 9.0 m where the response is markedly higher. This indicates presence of clay in the surrounding formation. The natural gamma log on the whole shows uniform packing of the gravel around the filter tube.

The filtration velocities encountered are quite low, varying from a minimum of 1.53 cm/d near the bottom layers to a maximum of 6.48 cm/d just below the filter. The variation of $v_f$ values along depth can be seen in relation to sub-surface geology of the area (Figure 18).

Whatever water is able to seep through the upper confining layer of clay and decomposed matter, will cause a faster movement in the layer just below the confining layer. The decrease of filtration velocity in deeper layers is the result of presence of finer sediments and more consolidated layers. As such, the water level gradient and differential water head in the upper and lower layers is quite low in the area.

The direction of water flow as measured by tracer method is towards the complex of IPT. The general flow of water in the region seems to be towards old Jaguaré stream and eventually towards Rio Pinheiros(25).

While extrapoling the results, it can be said that the filtration velocities in the immediate vicinity of the waste disposal site of IPEN will be only slightly more than encountered at IPT-complex which is 850 m away at a lower topographical level. The difference in topographical level being only 25 m.

It needs to be determined whether the direction of ground water flow at waste disposal site is towards old Jaguaré stream or towards IPT complex. The local topographical features indicate that the flow would be more so towards the old Jaguaré stream. The whole drainage eventually seems to be flowing towards the general direction of flow in the region i.e., towards Pinheiros river.

The average filtration velocity around the IPT complex is 3.66 cm/d. If the maximum of the filtration velocity i.e., 6.48 cm/d, encountered at IPT complex is taken as an average for waste disposal site of IPEN, the subsequent analysis of evaluation of the radioactive waste disposal site is not going to be far from reality.

With the filtration velocity of 6.48 cm/d and assuming an average porosity of the local sediments to be 35%, the general flow of ground water i.e. stage speed comes out to be 18.51 cm/d. This means that the ground water front will take about 2431 days to reach upto old Jaguaré stream, situated 450 m away. During this time the potentially most hazardous radioisotopes, cesium-137 and strontium-90, if released to ground, would decay by a factor of 0.86 and 0.85 respectively. Further, considering the retention of the radioelements by clay mineral content of the local soils, the concentration of the radioactive pollutant in the ground water stream is going to be significantly reduced at the point of emergence, i.e., the old Jaguaré stream or Pinheiros river. Values of distribution coefficients for radiocesium and radiostrontium can be safely assumed to be of the order of 1000 and 30 respectively. Empirically, the velocity of ground water can be correlated with velocity of radionuclide $v_R$ by the following expression:

$$\frac{v_R}{V} = \frac{1}{1 + \frac{\rho}{f} K_d}$$

where $\rho$ is the bulk density of the formation, f the porosity of the formation and $K_d$ the distribution coefficient for radionuclide in question.

While denoting a value of 1.8 to the bulk density, it can be said that polluted fronts of radiocesium and radiostrontium will move $1.94 \times 10^{-3}$ and $6.44 \times 10^{-3}$ times slower respectively than local ground water. While evaluating the waste disposal site of IPEN geohydrologically and from the point of view of migration of radionuclide pollutants, it can be said that:

- the disposal site is characterized with good soil cover favoring retention of radionuclides,
- water table at the site is fairly deep by virtue of its location at higher topographical level than its surroundings;
- ground water velocity in the region is quite low, thus resulting in longer travel times of the radioactive pollutant and their self decay;
- there is absence of possibilities which might elevate or change the water table conditions in the region significantly;
- there is absence of ground water use in the vicinity of the waste disposal site.

As and when monitoring wells in the waste disposal site are installed, additional measurements of filtration velocity and direction of ground water flow can be undertaken under various seasonal conditions of the local water table. Such a study is necessary and imperative before planing future radioactive waste disposal operations. Provisions of monitoring wells may call for initial financial investments but in a matter of radioactive waste management it is wise to overlook the cost considerations and lay stress on long term enviromental safety provisions.

In the investigations reported here, provision was not made to stop any vertical flow in the borehole during measurement of dilution rate. The results of filtration velocity along the depth of the borehole, indicate liklihood of presence of vertical flow but it may not be so prominent to affect the $v_f$ measurements noticeably.

In the construction of monitoring wells, care need be taken while making a choice of the filter tube and in providing the graded gravel pack around the filter tube. In the present investigations the data of construction of the well in which measurements were made reveal that permeability of the filter and the gravel pack $k_2$ are equal. This could have been avoided and a more favorable situation, $k_1$ being greater than $k_2$, could have been possible by choosing a filter tube of larger and closer perforations and appropriately graded gravel size.

With improved equipment for field work it should be possible to undertake similar work of determination of rate and direction of ground water for variety of investigations of engineering geology, water resources and ground water pollution.

Taking the average value of 3.66 cm/d of filtration velocity and the reported(25) value of hydraulic gradient $1 . 3 \times 10^{-2}$ (average), the permeability of the aquifer calculated from the relation

$$v_f = k \ . \ I$$

comes out to be $3 . 26 \times 10^{-3}$ cm/s. The permeability of the aquifer, as determined by conventional pumping tests carried out in the past, is reported to be $8 . 5 \times 10^{-4}$ cm/s. Thus, there is quite good agreement between the results obtained by tracer dilution technique and the pumping test.

Initially it was planned to determine transit time by multiwell techniques(1) while making use of the existing piezometers. If tracer was injected in the central well and was monitored in the perforated portion of the deeper piezometers, the transit time could be greater than 125 days for travelling 10 m distance in the direction of flow. It is to be noted that the piezometers are provided with the perforations only in their bottom portion of 1 meter. For determining such transit times a radioactive tracer of half life comparable to the duration of the experiment need to be used. There are not enough piezometers where the tracer could be monitored radially in the probable direction of flow. Because of very low filtration velocity and lack of radial array of piezometers, the injection of radiotracer of long half life in concentrations that may create environmental problems was not considered worthwhile. Hence the idea of determining transit time by two well technique was abondoned.

For similar reasons, the determination of aquifer parameters by two well pulse techniques(17) i.e., injecting radiotracer in a piezometer or in the well itself and then pumping out the water from the central well, was considered a futile exercise. Although not much data on multiwell pulse technique have been published, however, their application is worth considering where local geohydrological conditions meet the underlying conditons of validity of the techniques.

## 9 – CONCLUSIONS AND RECOMENDATIONS

It is concluded that in the vicinity of radioactive waste disposal site of IPEN,

- the filtration velocity of ground water is of the order of 6 . 48 cm/d
- the distance velocity of ground water (assuming 35% porosity) is 18 . 51 cm/d. Thus the ground water will take about 2431 days to reach old Jaguaré canal towards which the local drainage appears to be seeping.

Geohydrologically, the radioactive waste diposal site at IPEN has the requisite favorable characteristics viz, good soil cover for retention of redionuclides, deep water table and low ground water velocities.

For detailed geohydrological evaluation, post operational environmental monitoring and maintanence of the diposal site, provision of following will be necessary:

- adequate levelling of the waste disposal area to avoid further erosion of the land
- surface drains around the periphery of the proposed individual disposal trench facility to avoid precipitation run-off entering the trench area;

- fencing around the entire waste disposal area to stop any undesirable entry of persons from surrounding population;
- surface drains around periphery of the site to avoid external run-off entering the disposal site;
- an adequate grid of monitoring wells in the downstream direction. The distribution of monitoring wells can be decided after locations of proposed waste disposal trench facilities are finalised. The monitoring wells need be constructed with proper choice of filter tube and gravel pack. Instead of galvanized iron pipes, special metal filters coated with pvc, or a perforated high density polyethylene pipe, can be used for more durability.

## ACKNOWLEDGEMENT

Thanks are due to the staff of Instituto de Pesquisas Tecnológicas (IPT), for providing help in carrying out the field experiments.

## RESUMO

~~O presente relatório~~ Descreve-se o método de determinação da velocidade e da direção do fluxo da água subterrânea mediante o uso de traçadores radioativos. São apresentados e discutidos: a influência dos diversos parâmetros que intervêem no fenômeno; a aplicabilidade do método no estudo de problemas geohidrológicos; e a comparação desse método com o método clássico de bombeamento.

A *primeira* aplicação do método de diluição, para a medição do fluxo, feita pelo Centro de Aplicações de Radioisótopos e Radiações na Engenharia e na Indústria, CARREI, foi no estudo do movimento da água subterrânea na *área de disposição de resíduos radioativos* do Instituto de Pesquisas Energéticas e Nucleares, IPEN. Nesse local, foi feito um estudo geohidrológico.

As determinações da direção e do fluxo da água subterrânea, foram feitas num poço, o mais próximo disponível, localizado a cerca de 850 metros de *distância da área de disposição de resíduos radioativos*.

Os traçadores radioativos utilizados nas *medições da velocidade do fluxo foram* o $^{131}I$ e o $^{82}Br$ e para a determinação da direção foi utilizado o $^{51}CrCl_3$, por ser um traçador com boas características de adsorção.

Os equipamentos de campo consistiram em sondas de cintilação gama, escalímetros/integradores BASC, sistemas de injeção do traçador e o colimador para a sonda cintiladora, com um sistema de orientação.

Foi feita uma perfilagem gama para verificar a construção do poço e para ter uma idéia do perfil *litológico* do local. Também foram feitas estimativas da velocidade da água subterrânea e do tempo de trânsito dos radionuclídeos, no local de disposição de resíduos radioativos.

A velocidade média de filtração, obtida num local situado a cerca de 850 metros de distância dessa área, foi de 3,66 cm/dia, sendo que o fluxo da água subterrânea dirige-se ao antigo canal do Jaguaré.

Estimando-se a densidade global em 1,8 g/cm$^3$, a porosidade igual a 35% e coeficientes de distribuição igual a 1000 para o $^{137}Cs$ e 30 para o $^{90}Sr$, fizeram-se as seguintes análises com respeito a área de disposição de resíduos radioativos:

velocidade de filtração da água subterrânea = 6,48 cm/dia

velocidade intersticial da água subterrânea = 18,5 cm/dia

tempo de chegada da água subterrânea ao ponto mais próximo do antigo canal do Jaguaré = 2431 dias

$$\frac{\text{velocidade do radionuclídeo}\,(^{137}\text{Cs})}{\text{velocidade da água subterrânea}} = 1{,}94 \times 10^{-3}$$

$$\frac{\text{velocidade do radionuclídeo}\,(^{90}\text{Sr})}{\text{velocidade da água subterrânea}} = 6{,}44 \times 10^{-3}$$

Os valores das permeabilidades determinadas no campo são as seguintes:

determinada com o uso de traçadores radioativos $= 3{,}26 \times 10^{-3}$ cm/s

determinada com o método do bombeamento $= 8{,}50 \times 10^{-4}$ cm/s

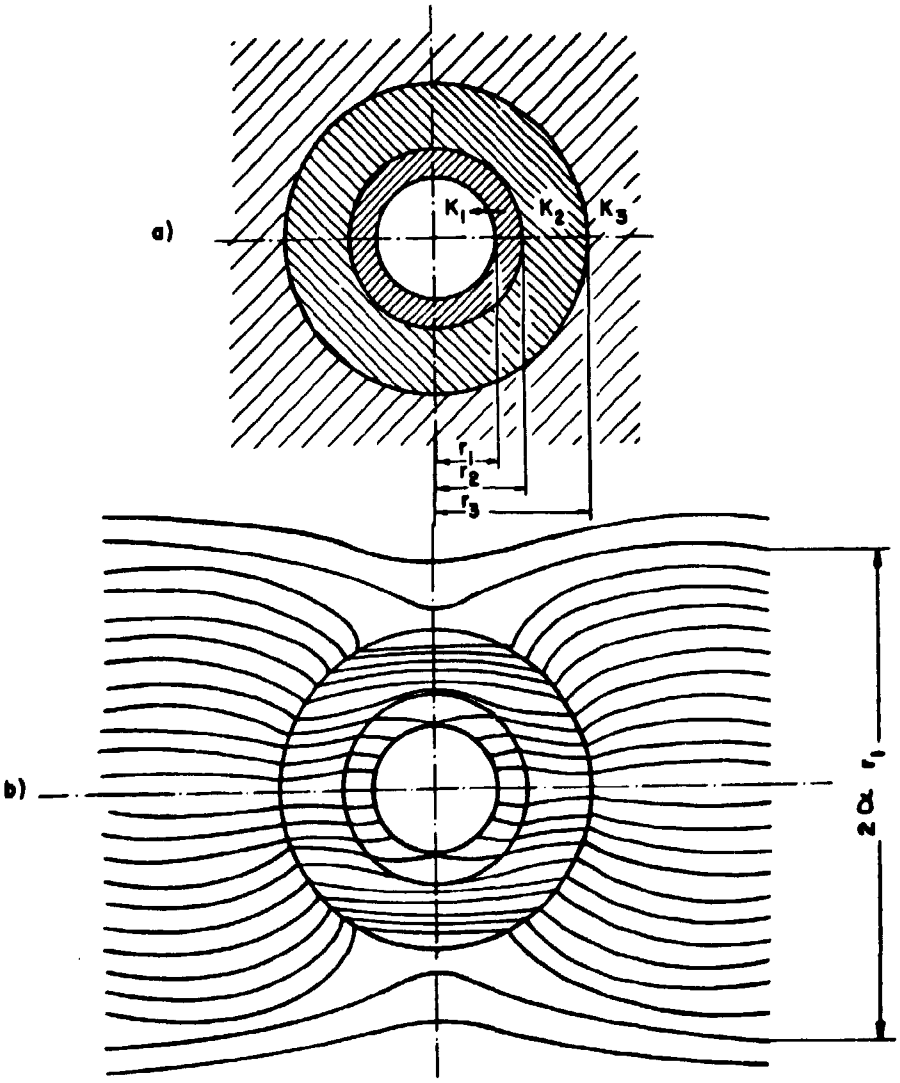
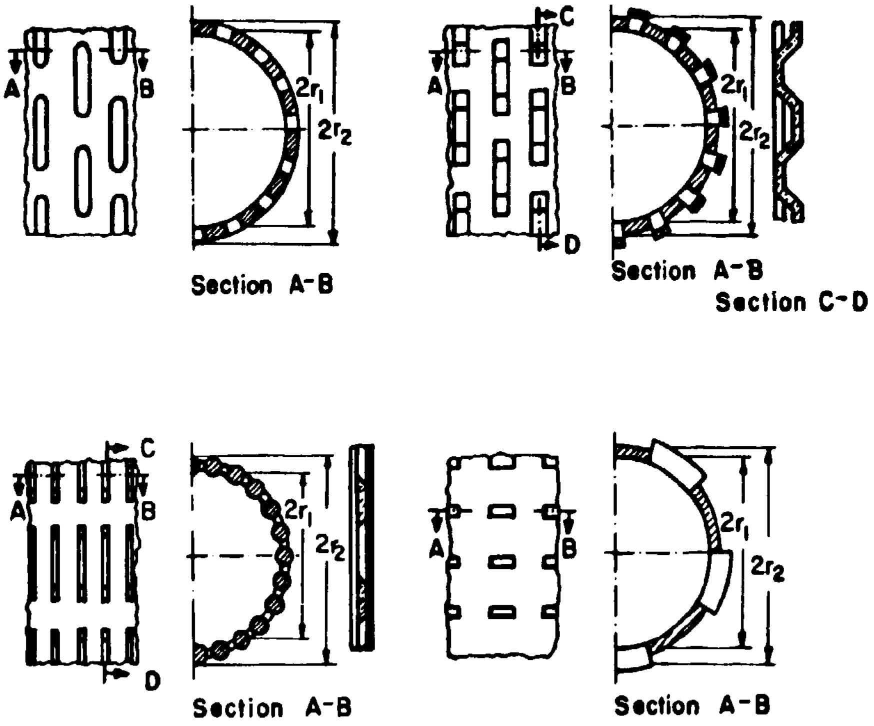


**Figure 1** – Construction of borehole with gravel pack in homogeneous aquifer.

$r_1$ – inner radius of filter tube — $k_1$ – permeability of filter tube

$r_2$ – outer radius of filter tube — $k_2$ – permeability of gravel pack

$r_3$ – radius of boring — $k_3$ – permeability of aquifer



Section A-B

Section A-B

Section C-D

Section A-B

Section A-B

Figure 2 – Various recommended designs of filter tubes.

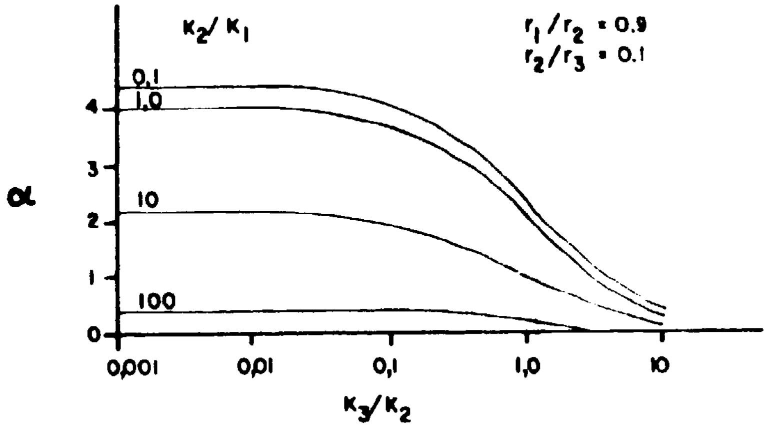


**Figure 3** – Dependence of α on $k_3/k_2$ (parameter $k_2/k_1$ when $r_2/r_3 = 0.1$).

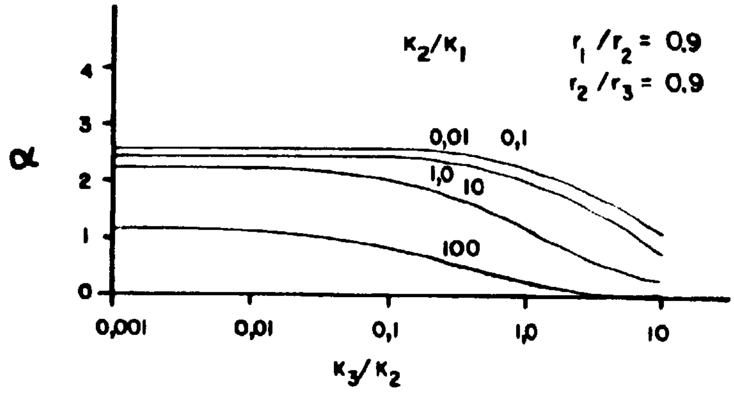


**Figure 4** – Dependence of α on $k_3/k_2$ (parameter $k_2/k_1$ when $r_2/r_3 = 0.9$).

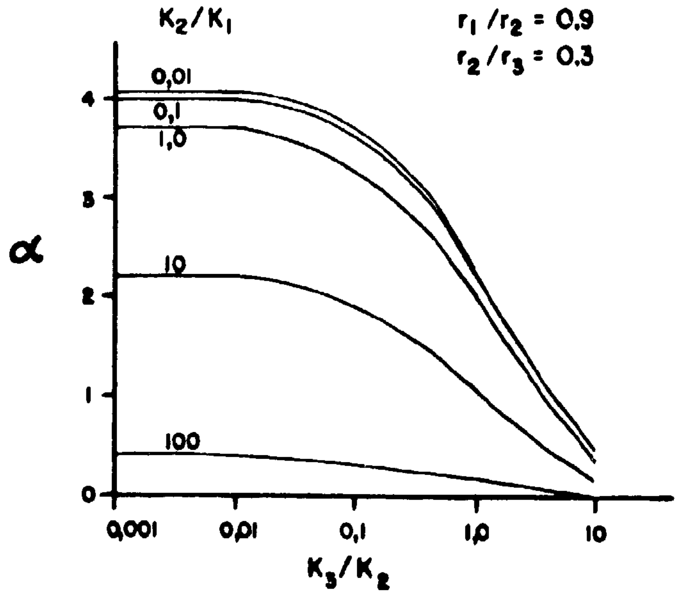


**Figure 5** – Dependence of α on $k_3/k_2$ (parameter $k_2/k_1$ when $r_2/r_3 = 0.3$).

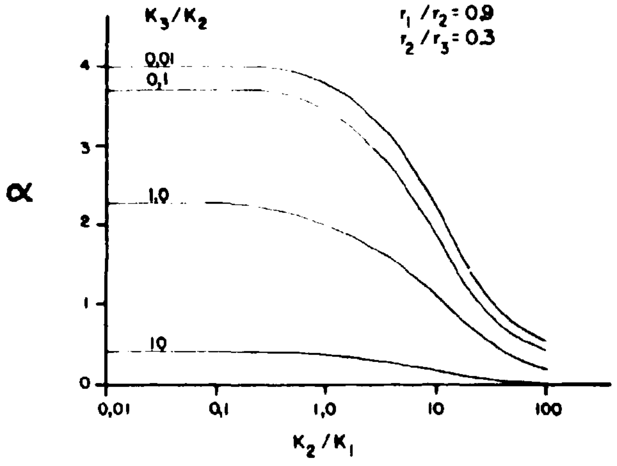


Figure 6 – Dependence of $\alpha$ on $k_2/k_1$ (parameter $k_3/k_2$).

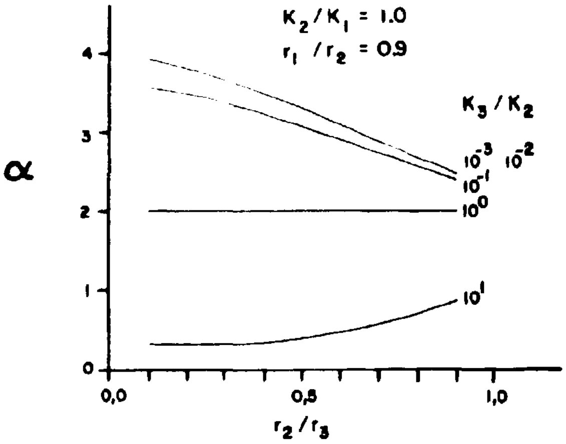


Figure 7 – Dependence of $\alpha$ on $r_2/r_3$ (parameter $k_3/k_2$).

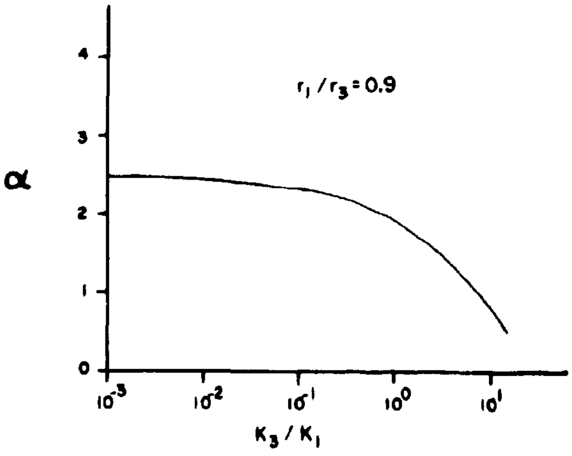


Figure 8 – Dependence of $\alpha$ on $k_3/k_1$ (parameter $r_1/r_3$).

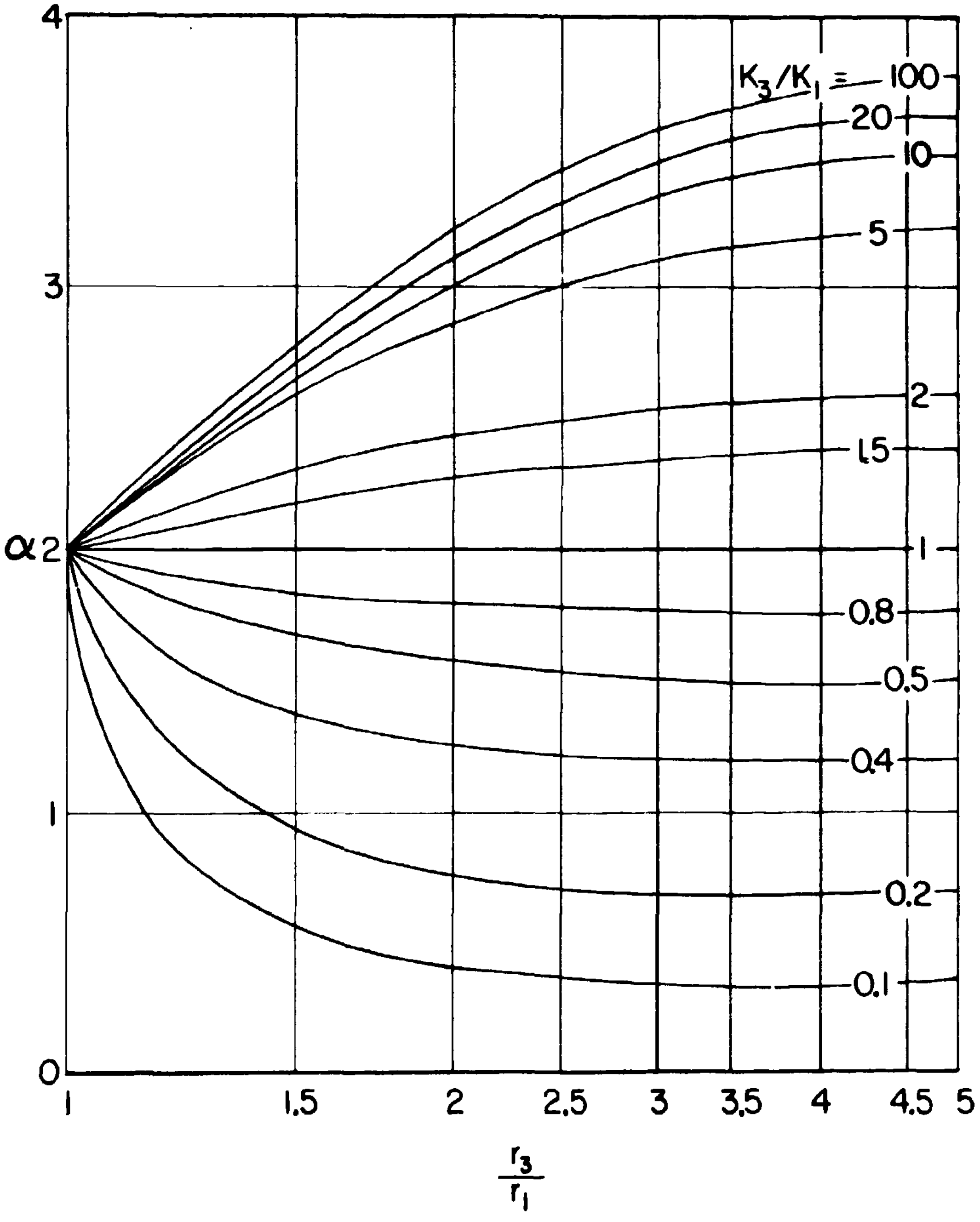


Figure 9 – Ogilvi's diagram, dependence of α on $r_3/r_1$ (parameter $k_3/k_1$) in absence of gravel pack or filter tube.

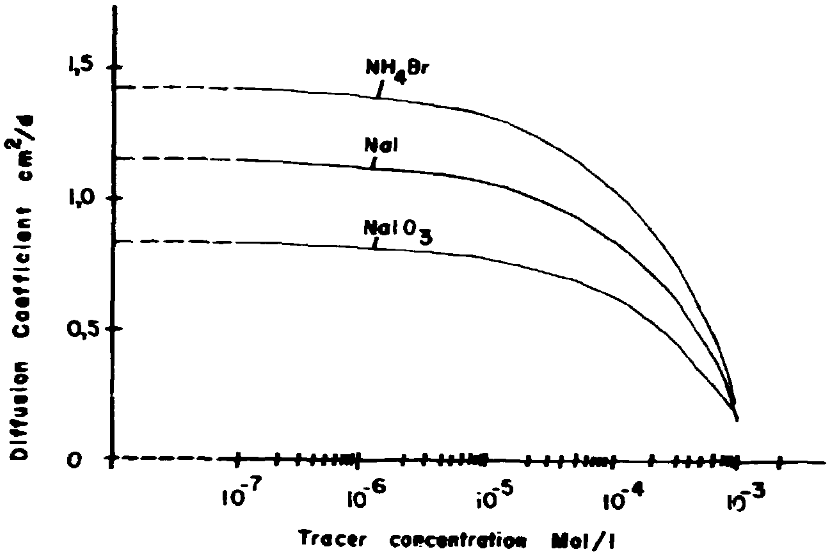


Figure 10 – Dependence of diffusion coefficient on tracer concentration[13]

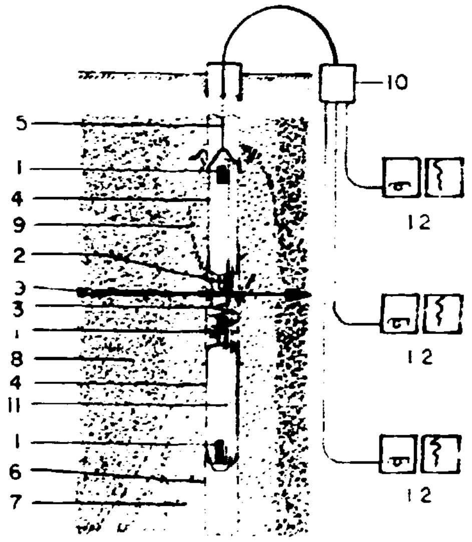


Figure 11 – Measuring system recommended for determining filtration velocity in ground water wells[9].

1 – Scintillation Detector
2 – Tracer Injection Device
3 – Mixing Device (coil)
4 – Rubber Seal
5 – Waterproof Electric Cable with Compressed Air Line
6 – Filter Tube
7 – Gravel Pack
8 – Aquifer
9 – Ground Water Stream Line
10 – Surface Controls for Mixing Device and Injection Device
11 – Pressure-Equalizing Tube

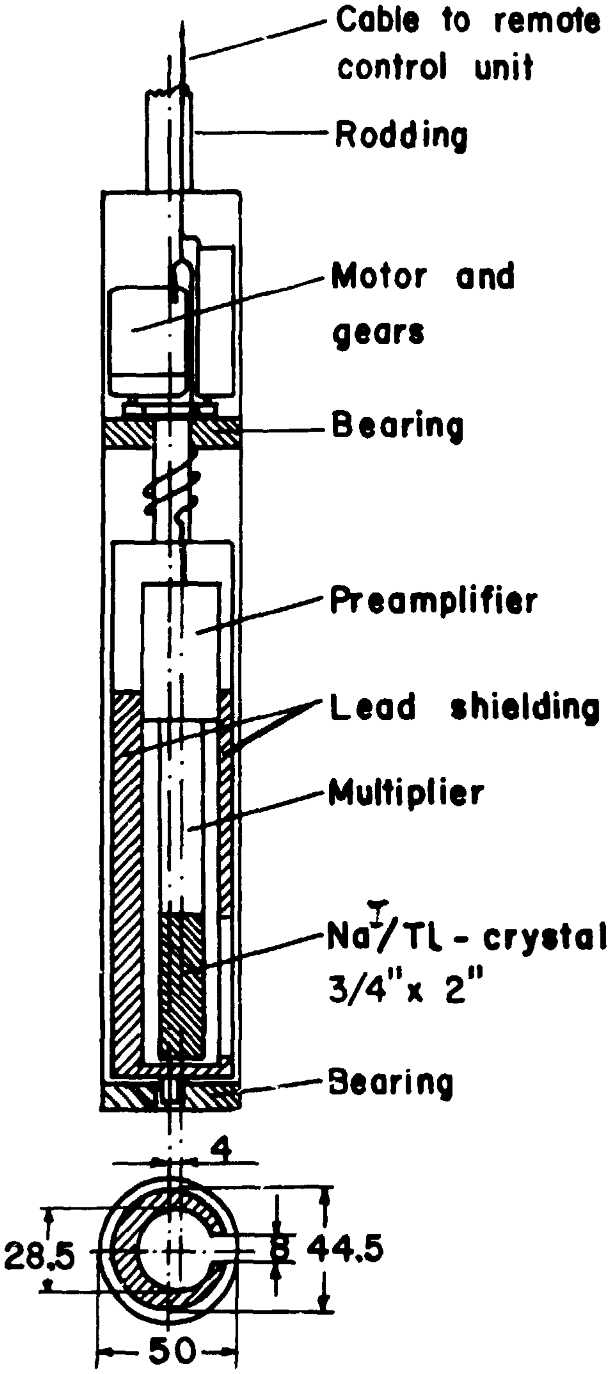


Figure 12 – Scintillation-counter probe for measuring direction of ground water flow (dimensions in mm).

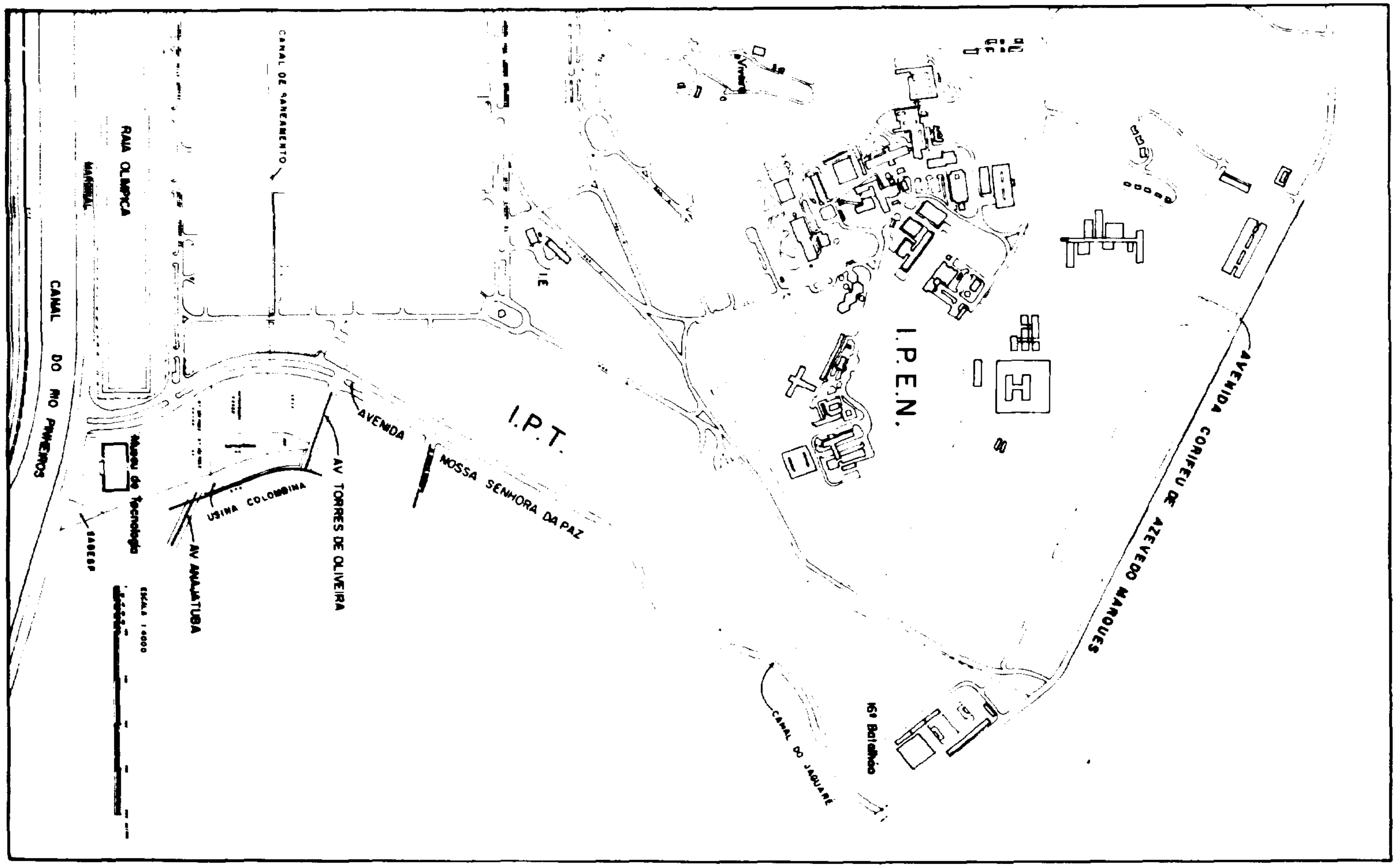


Figure 13 – Location map of Instituto de Pesquisas Energéticas e Nucleares (IPEN), Instituto de Pesquisas Tecnológicas (IPT), Jaguaré Channel, Raia Olimpica (USP) and Pinheiros River.

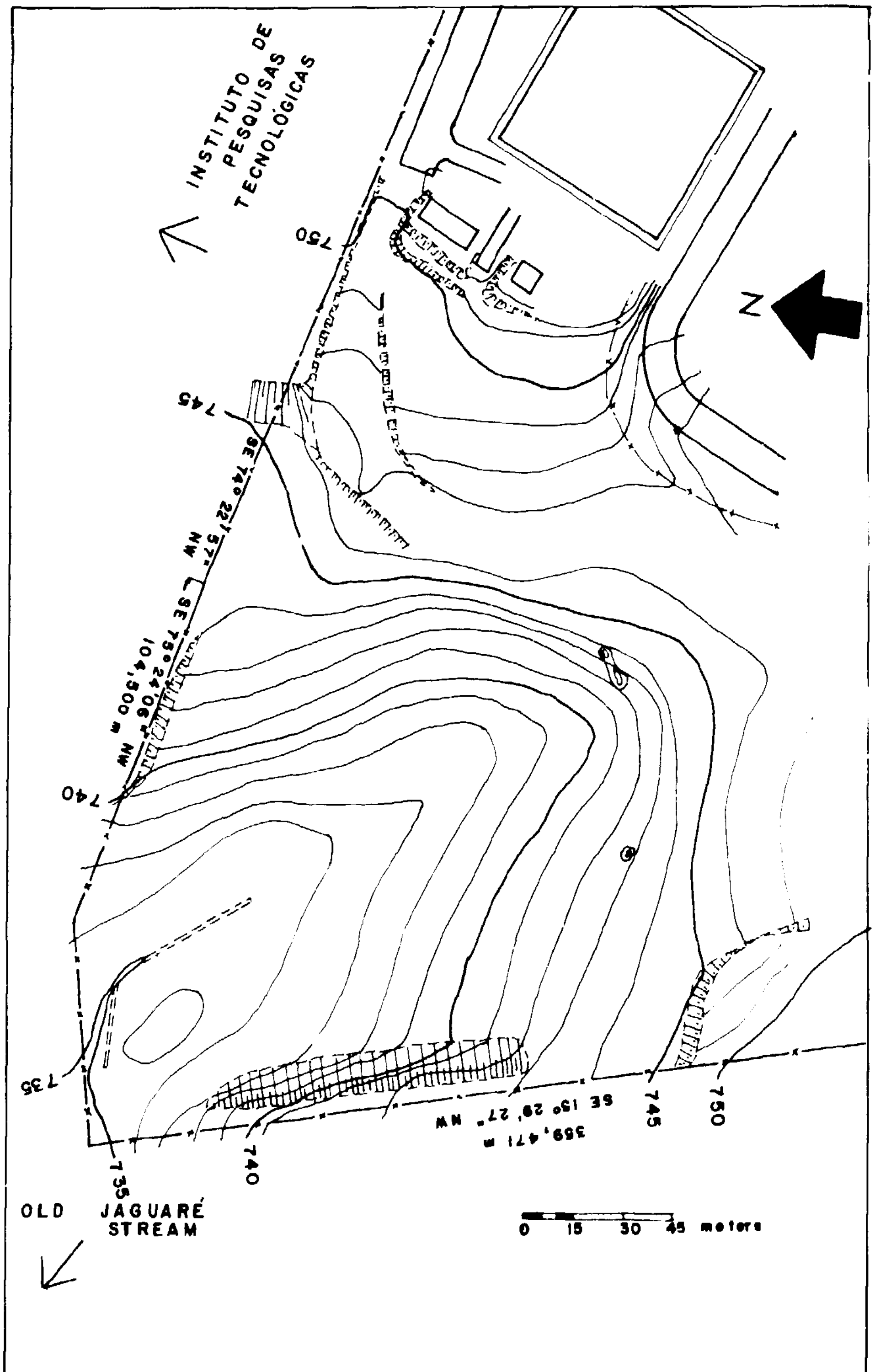


Figure 14 – Topographical features around probable area of radioactive waste disposal at Instituto de Pesquisas Energéticas e Nucleares.

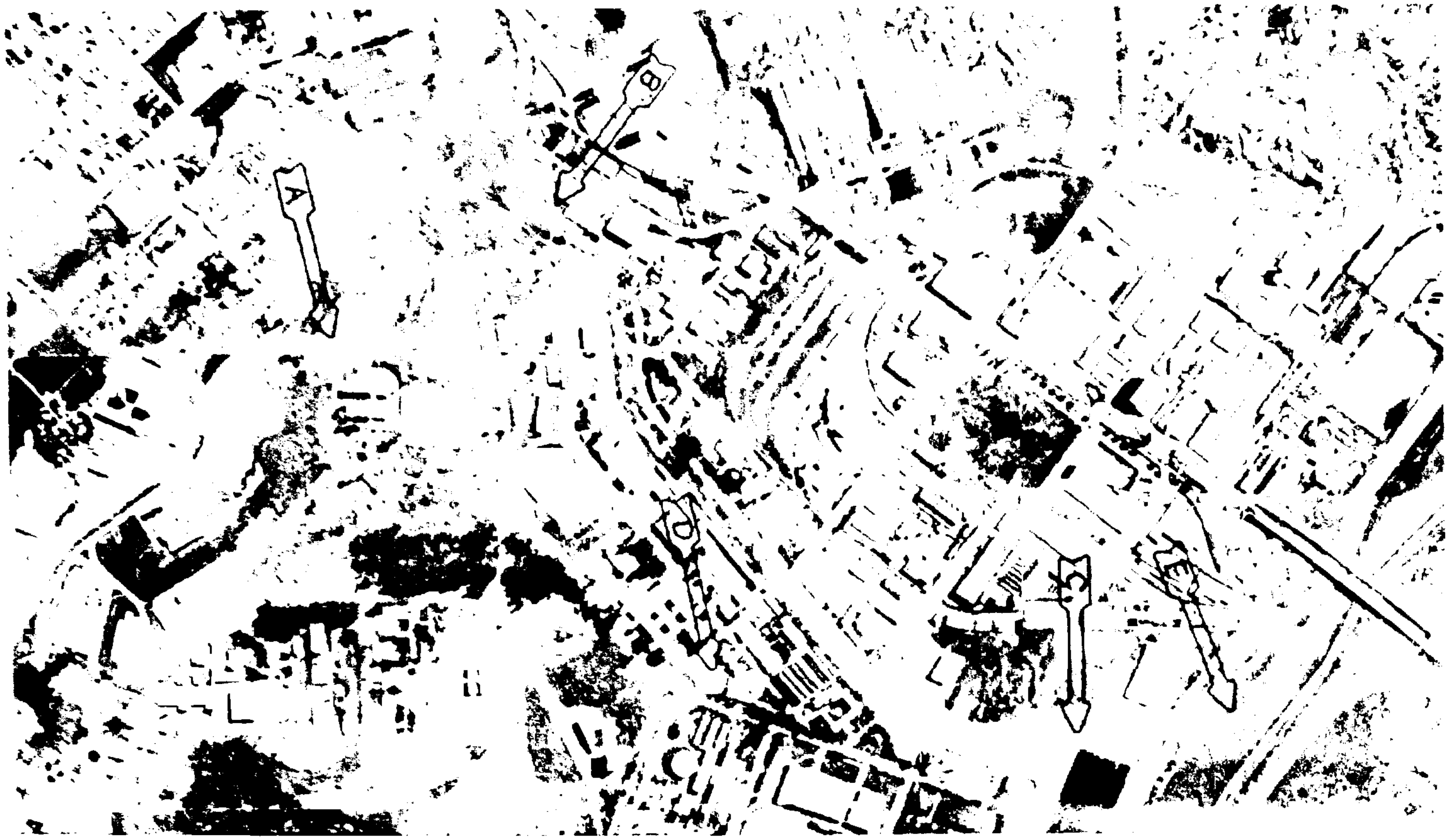


Figure 15 – Areal view around Instituto de Pesquisas Energéticas e Nucleares.

A: Probable Area for Radioactive Waste Disposal.
B: Old Jaguare Stream.
C: Raia Olimpica of USP.
D: Site of Field Measurements Within the Complex. of Instituto de Pesquisas Tecnológicas.
E: Pinheiros River.

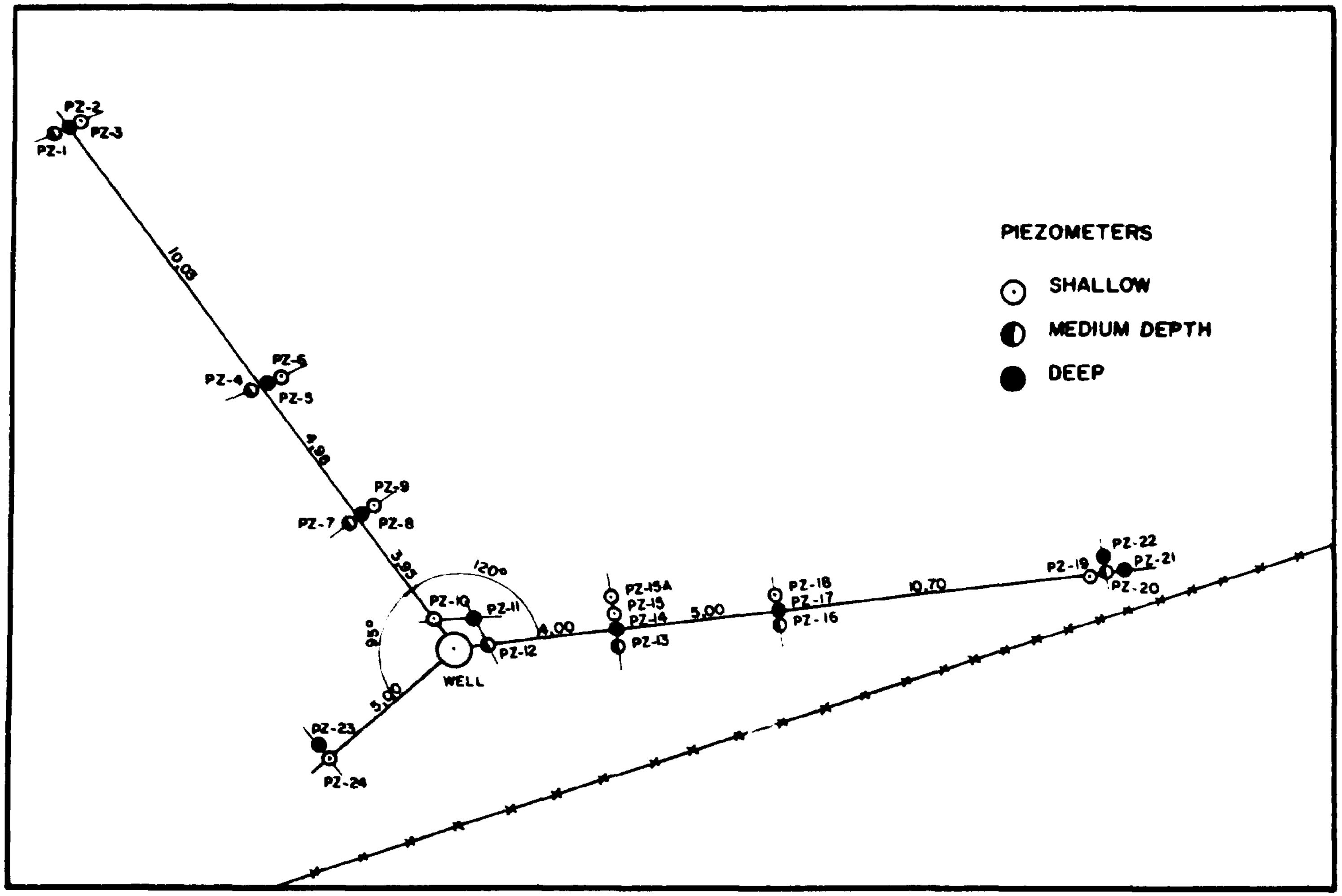


**Figure 16** – Location of the well where measurements were carried out(24).

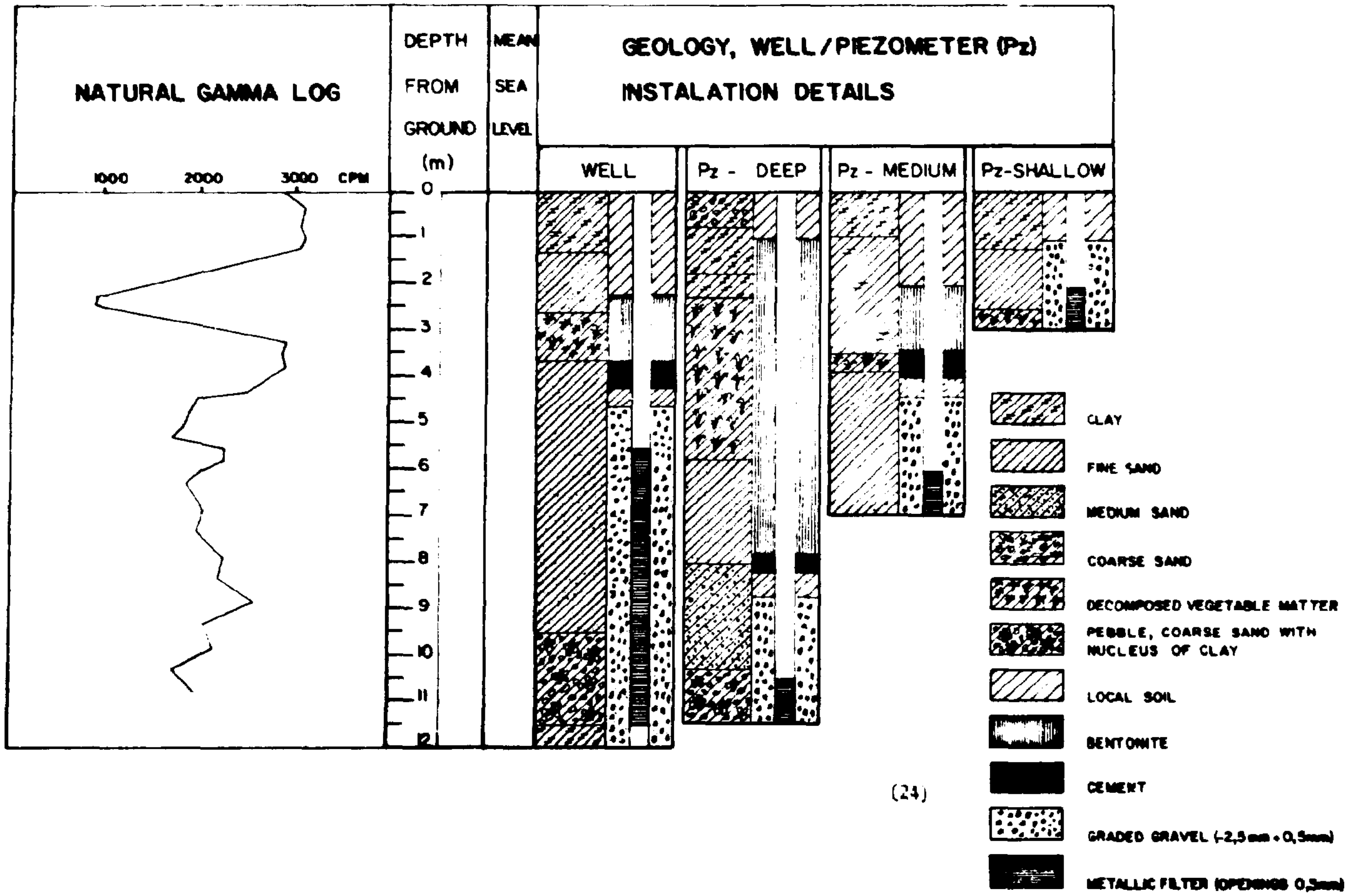


Figure 17 – Detail of construction of the well, piezometrs and local sub-surface geology$^{(24)}$.

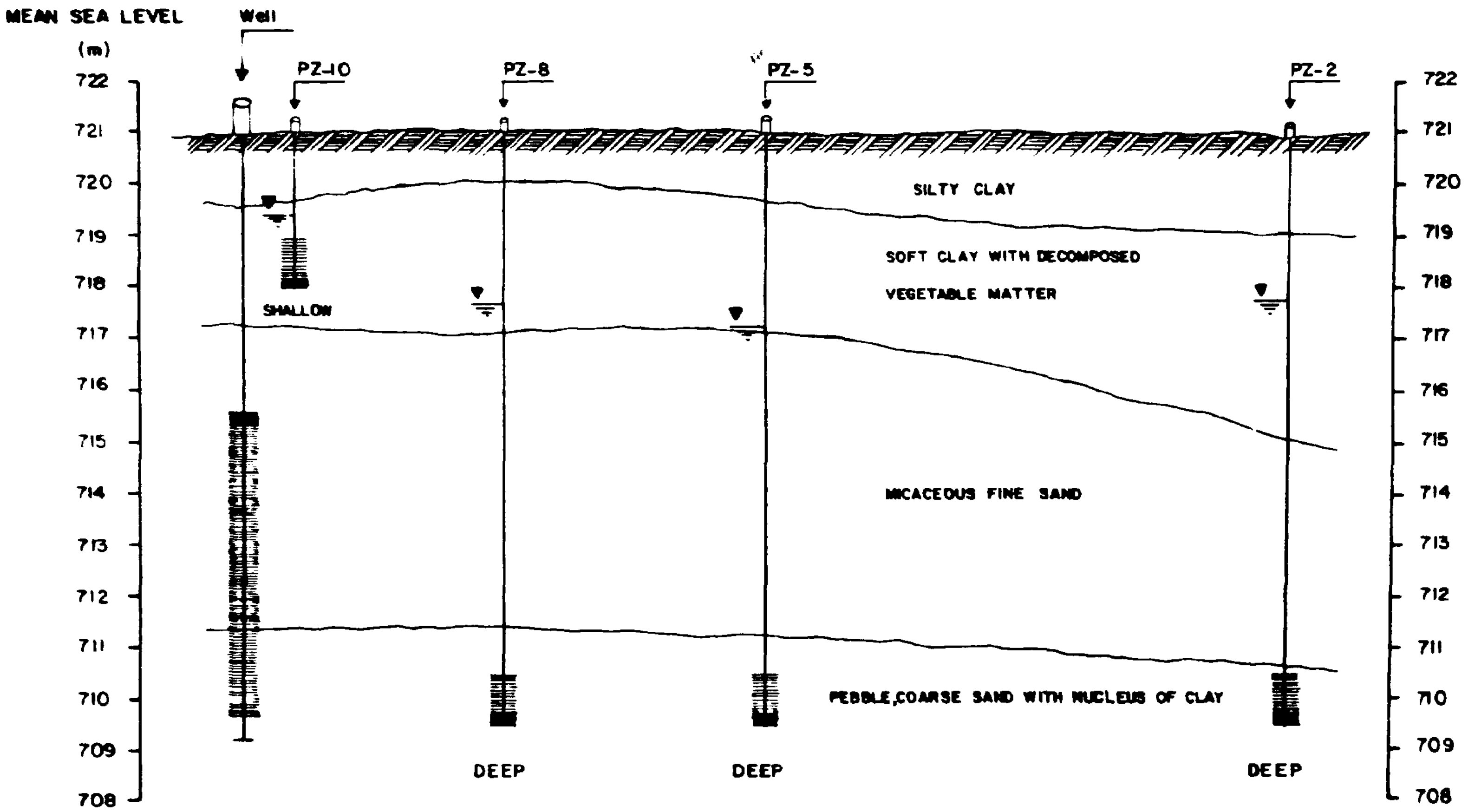
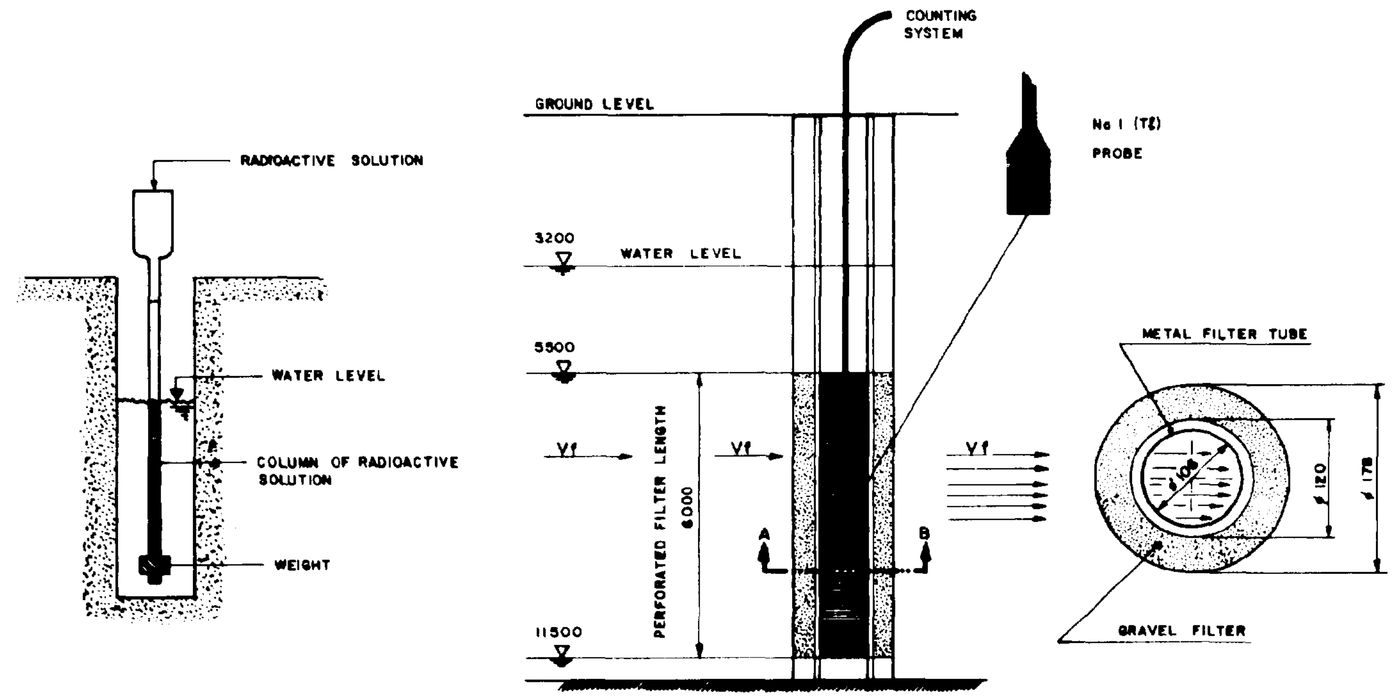


Figure 18 – Geological section of strata along piezometrs 10, 8, 5, 2(24).



(a) SYSTEM OF INJECTION

(b) LONGITUDINAL SECTION
SCALE 1:10

(c) TRANSVERSE SECTION A-B
SCALE 1:5

ALL DIMENSIONS IN mm

Figure 19 – Details of field information.
a – System of Tracer Injection Used.
b – Ground Water Level, Filter Length and Depth of Measurement.
c – Dimensions of Filter Tube and Gravel Pack.

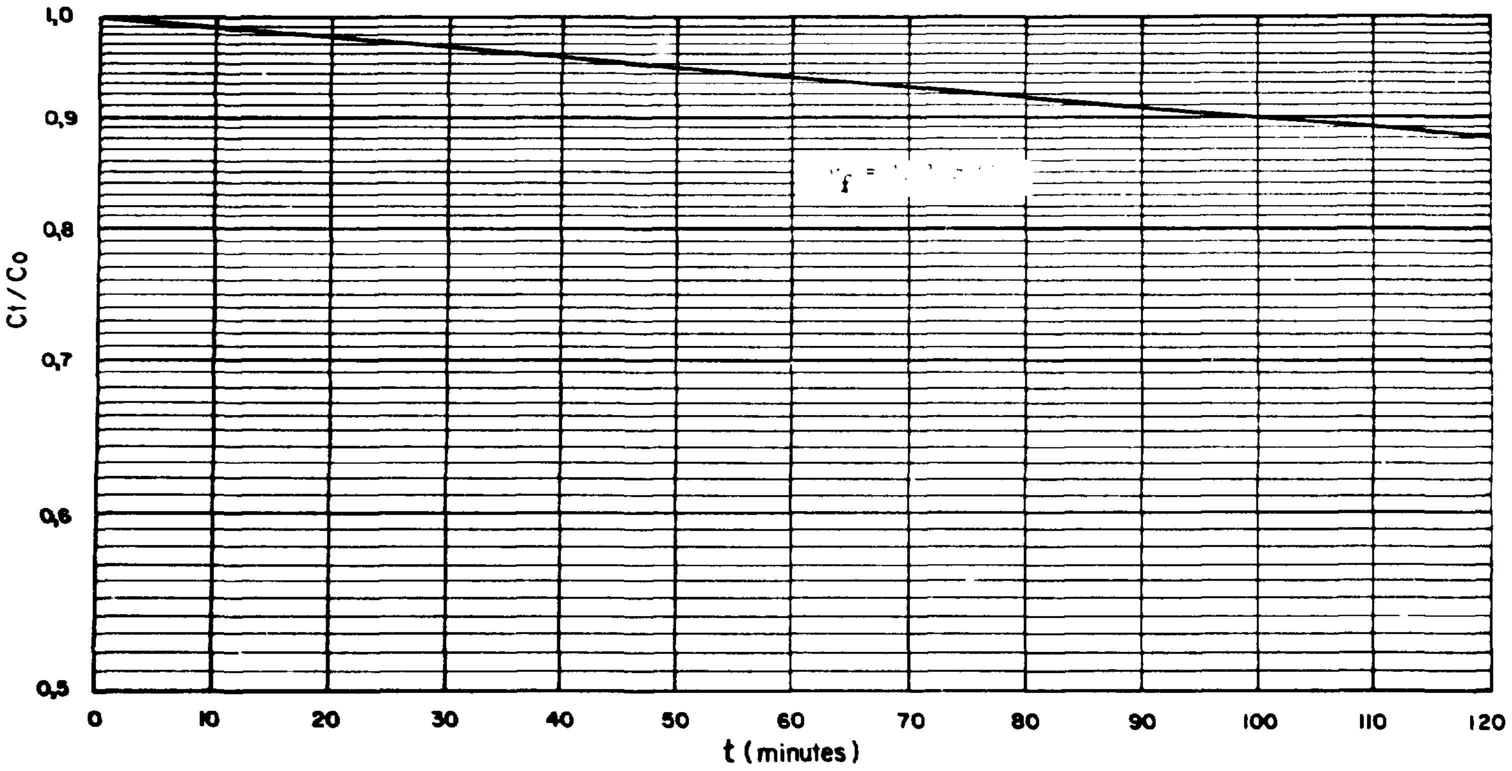


Figure 20 – Observed dilution curve for computing filtration velocity (iodine-131 was used as radioactive tracer).

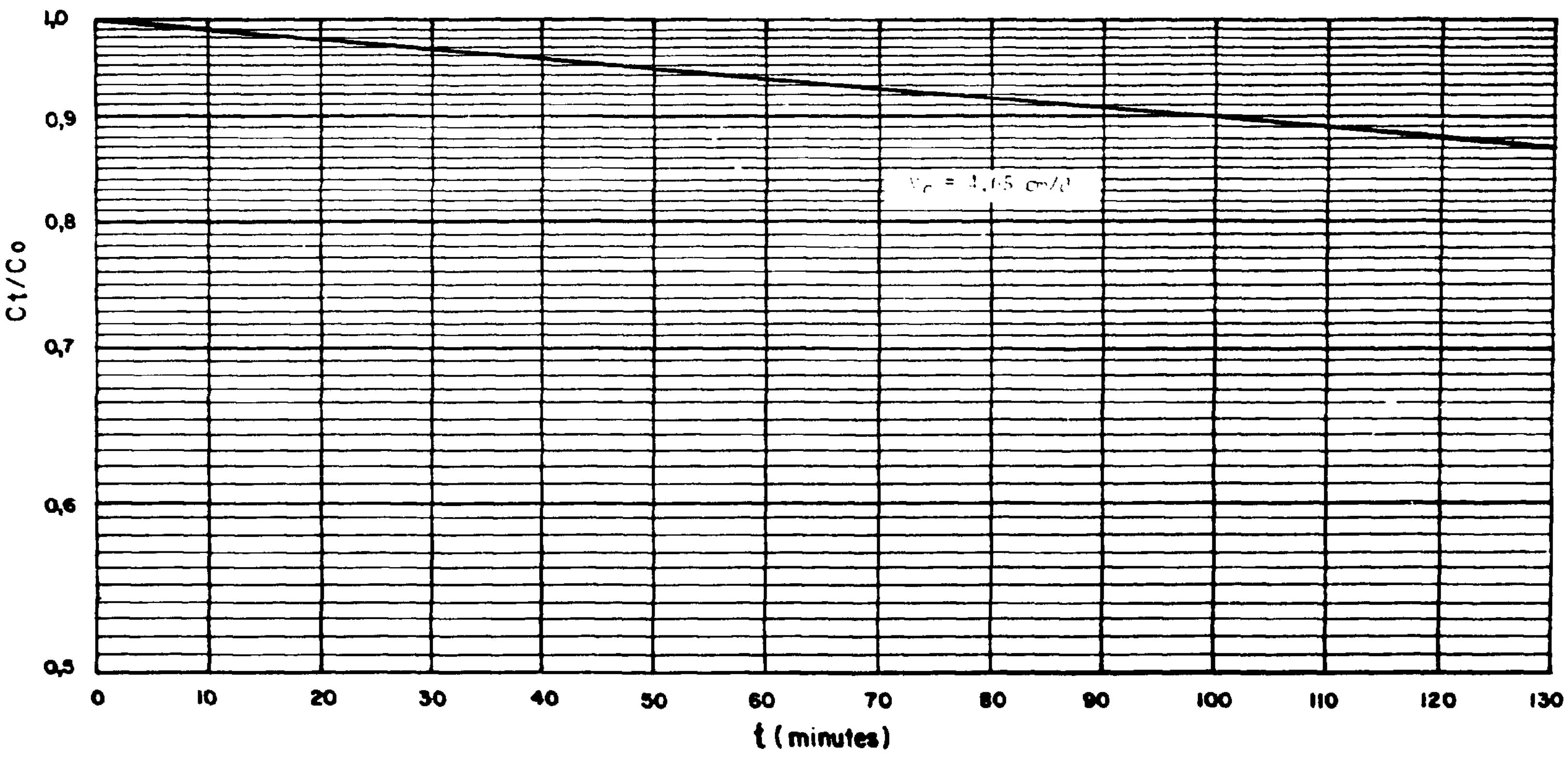


Figure 21 – Observed dilution curve for computing filtration velocity (bromine-82 was used as radioactive tracer).

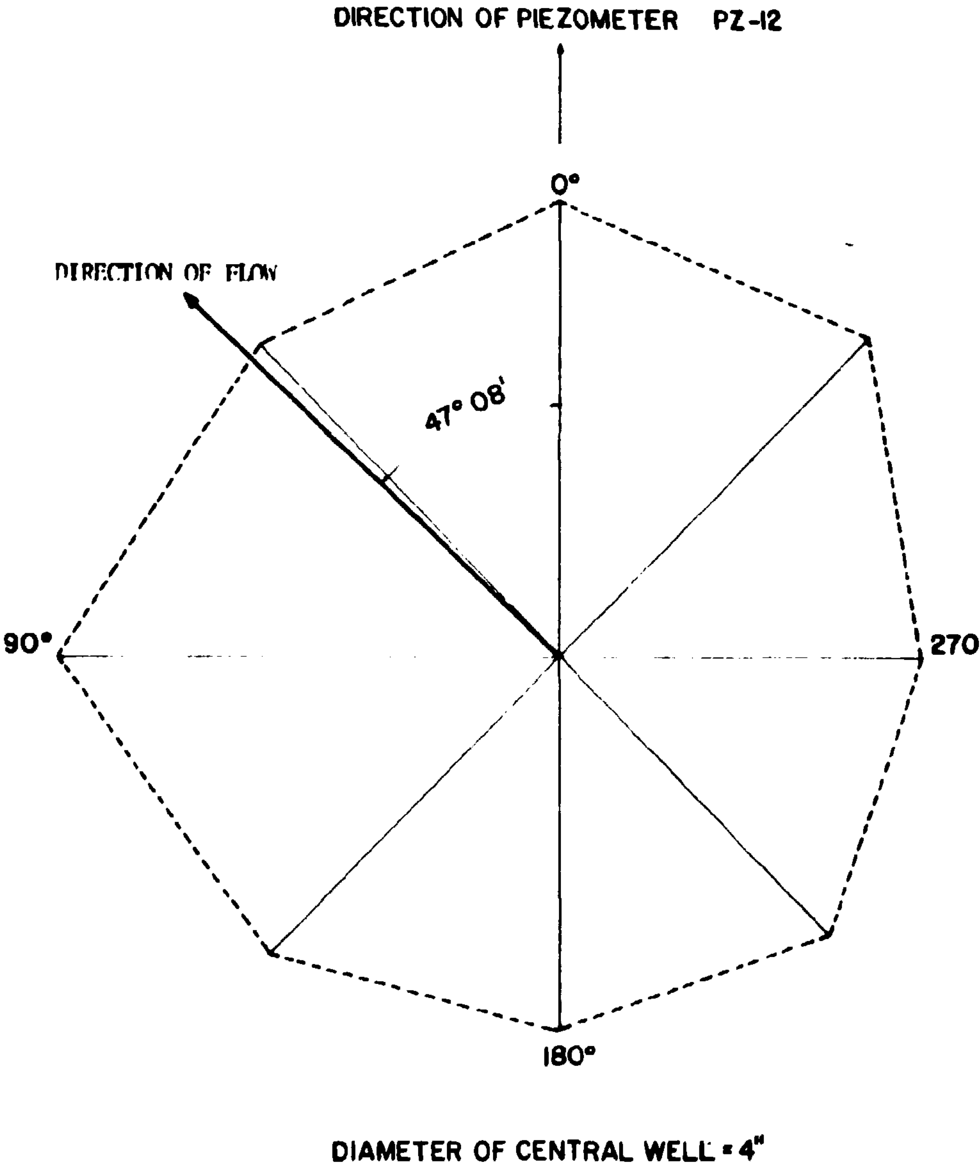


Figure 22 – Observed direction of ground water flow in the well (activity injected: 1 mCi $^{51}CrCl_3$).

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