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DETERMINATION OF VELOCITY AND DIRECTION OF GROUND WATER BY RADIOACTIVE TRACERS

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RESUMO

Utilizaram-se traçadores radioativos, junto com a técnica de diluição em poços, para a determinação da velocidade e direção do fluxo de águas subterrâneas. Estes parâmetros podem determinar-se em um único poço ou piezômetro. Neste trabalho apresenta-se uma descrição das técnicas de medição e experiências de campo num local próximo ao depósito de resíduos radioativos do IPEN. Para a determinação da velocidade da água subterrânea usaram-se Iodo-131 e Bromo-82, como traçadores radioativos. Para determinar a direção dessa água empregou-se o Cromo-51, na forma de cloreto.

Finalmente, apresenta-se uma resenha da aplicação dessas técnicas no estudo de problemas relacionados com a exploração, poluição de águas subterrâneas e engenharia geológica.

INTRODUCTION

Radioisotopes are normally used as tracers to determine characteristics of aquifers, viz. direction and velocity of water flow (HALEVY et al., 1967); vertical flow in stratified aquifer (DROST, 1970); stage speed (BATSCHE et al., 1970; MANDEL, 1960; BOROWCZYK et al., 1967); porosity and transmissibility (HALEVY and NIR, 1962).

Application of radioactive isotopes in ground water investigations is made via the single well and multiwell methods (HALEVY et al., 1967; BATSCHE et al., 1970). 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 paper describes, the technique of single well method and its application in the problems of ground water exploitation, ground water pollution and engineering geology. Measurements of velocity and direction of ground water in a well near the radioactive waste disposal site at IPEN are reported. These studies form a part of the project of IPEN of determining suitability of the site for radioactive waste disposal.

The well in which experiments were carried out is about 850 m away from the disposal site in the northern direction. It lies within the complex of IPT and was constructed by IPT for some of its earlier studies (IPT, 1976) in the region. The staff of Minas e Geologia Aplicada, IPT, extended their help in providing facilities for carrying out radiotracer experiments in the well, as a part of collaboration for application of isotope techniques in studies of geohydrology. Further studies, ie., determination of geological characteristics of the area near disposal site and supplementing these investigation with nuclear logging, etc., are in progress.

DETERMINATION OF VELOCITY OF GROUND WATER AND PRINCIPLE OF SINGLE WELL METHOD

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

$$v_f = k_3 . I \qquad (1)$$

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

$$v_f = n.\nu \quad (2)$$

A direct means of determining filtration velocity is the dilution method. In this method, the water in a borehole is labelled with a radioactive tracer solution and the dilution of the radioactivity 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:

$$v_a = -\frac{V}{Ft} \ln c/C_o \quad (3)$$

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 C_o and c.

The horizontal flow pattern in the aquifer is distorted owing to the presence of a borehole and the different flows therein. 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;

$$v_a = v_f + v_c + v_v + v_m + v_d \quad (4)$$

where, v_c - apparent filtration velocity caused by density effects (concentration, temperature, etc)

v_v - apparent filtration velocity caused by vertical currents

v_m - " " " " " artificial mixing

v_d - " " " " " molecular diffusion of the tracer

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

$$\alpha = Q_a/Q_b$$

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 (ie. in the absence of the borehole). In the absence of all other flows but horizontal

$$v_f = -\frac{V}{Ft} \ln c/Co \quad (5a)$$

$$V_f = \frac{-\pi r_1}{2\alpha t} \ln c/C_o \quad (5b)$$

Borehole construction and calcutation 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 and r_1 and if the respective permeabilities of the filter tube, gravel pack and the formation are k_1, k_2 and k_3, then application of the potential theory to this borehole gives the folowing expression for α (IfR, 1965; KOCH, 1966)

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

Inthe absence of a gravel pack (see Fig. 1) $r_2=r_3$. Then, the equation (6) is reduced to Ogilvi's formula (OGILVI, 1958).

$$\alpha = \frac{4}{1+(r_1/r_2)^2 + k_2/k_1\left[1-(r_1/r_2)^2\right]} \quad (7)$$

Permeability of the filter tube k_1, can be measured from experimental as well as theorical model tests (KOCH et al., 1967). Various investigations (HALEVY et al., 1966; KRATZSCHMAR, 1966) have made computer calculations for α, as a function of the parameters k_2/k_1 and k_3/k_2. The results of computer calculations made from equation (6) show that α remains independent of the parameters k_2/k_1 and k_3/k_2 and depends only on the radius r_1, r_2 and r_3, and hence can be calculated with sufficient accuracy (10%), if the conditions, are fulfilled.

In practice, it is revealed that the condition $10\ k_3 \ll k_2$ is satisfied in most of the cases. If the conditions $k_1 \gg k_2$ is not satisfied, α must be calculated from the values of k_1 and k_2 by equation (6). For this prupose values of k_1 and k_2 will have to be determined by laboratory tests or taken from the available literature.

For the case of the borehole without gravel filter, it can be shown that α is independent of k_3 for $k_1 \gg 10\ k_3$. In the event that $k_1 = k_3$ (ie, the worst case), a maximum deviation of 20% for α must be taken into account. This is admissible seeing the range of accuracy required in practice.

Effect of tracer diffusion

Equation (4) shows that the diffusion of the tracer plays a part in determinig dilution rate v_a.

Laboratory model experiments (IfR, 1965) 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

$$V_f = \frac{v_a - v_d}{\alpha} \qquad (9)$$

provided there are no other disturbing parameters (ie. v_c, v_v, v_m are negligible).

Effecte of probe dimensions

A correction in the dilution volume in the equation (5) due to the volume of the detector probe has been sugested by various workers (KLOTZ, 1966; KROLIKOWSKI, 1965). If the detector probe has a radius r_o then equation (5) becomes,

$$v_f = -\frac{(r_1^2 - r_o^2)\ \ln c/Co}{2\alpha . r_1 t} \qquad (10)$$

Experiments have shown that α-value remains independent of r_o/r_1 within the range of $0 \leq r_o/r_1 \leq 0.92$. 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 adsorption on the walls and by tracer outside the measuring volume. It is preferable to use a probe whose diameter does not exceed half of the filter tube diameter.

Effect of mixing

The derivation of the equations (3), (5) and (10) is based on the assumption that the distribuition 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-logarithmic straight lines of different slopes are often encountered. Only with filtration velocity less then 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 an 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 α-value. Too intense mixing, may-especially if very small velocities are involved-lead to additional disturbances of the flow field or forcing the tracer out of the measuring volume.

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 or when the borehole penetrates stratified water bearing formation. 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 flow.

However, it is possible, through technical measures to minimise the vertical flow such that they do not disturb the measurement result . To eliminate vertical flow within the filter tube, use of packer to seal the top and bottom of the dilution volume has been seggested by various workers (HALEVY et al., 1966;KLOTZ, 1966; GUIZERIX et al., 1963).

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 (DROST et al., 1968). 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 there by increase the α-value. Model and field tests have shown (KRATZSCHMAR, 1966) that with seals of length 10 and 25 cm. and a length of 25 cm. of the dilution volume, the increase of α-value amounted to about 10%.

The decrease in concentration of the tracer solution (ie. the counts of the 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.

Borehole dilution method is best suited to homogeneus formations like alluvial gravel and sands. In the presence of significant vertical flow or in fractured and karstic rocks the results of the dilution methods are utilizable normally only qualitatively. Even qualitative measurements are of immense practical importance in investigation 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 borehole of any diameter ($\simeq 1\ 1/2''$)
- it is economical to determine ground water velocity by the method.

Determination of direction of flow

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 direction-sensitive detector . 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 lead shield. The collimater window can be rotated continuously by means of a drive motor in the probe (IfR, 1966).

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^o .The reproductibility of the method in the field is better than 10%.

Application of dilution method in hydrogeological investigations

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

-ground water exploration (MAIRHOFER,1965 ; CHANDRA et al; 1976);
-well installation (KRATZSCHMAR, 1966);
-seepage from dams , reservoirs, rivers, canals (MOSER et al,1963 ;IfR, 1969 ; IYA , 1972) ;
-soil consolidation and load on ground water (BVFA, 1954) ;
-sanitary engineering ,waste disposal and pollution (CHANDRA et al; 1978) ;
-engineering geology (IfR,1965 ;DROST, 1971 ;IfR,1964/5/6/7/8/9 and 1970 ;DROST , 1972).

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 Universitaria.

The local topographical contours vary from 750 m to 735 m and are sloping in the north-west direction (see Figure 2) towards the course of old Jaguare stream which is about 450 m away from the disposal site.

Based on the records of various wells drilled in the past in the region of Jaguare, Cidade Universitaria and Butanta, the sub- surface geeology of the area can be generalized as following(HIDROGEOLOGICAS,S.C.,1972):

- 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 m- the thichness decreases in the western direction
- pre-cambrian crystalline basement with occurrence of cracks and fissures between 70 to 120 and 250 m
- the water table aquifer containing the rainfall infiltration consists of the first 10 to 15 m of the sediments.

Monitoring wells at the disposal site are planned to be installed in a grid pattern to establish local 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 meters away from the disposal site in the northern direction. The well and piezometers are located in the complex of IPT.

The main well is of 4" internal diameter while the diameter of the piezometers is $1^1/2$" 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 a graded gravel pack.

Determination of filtration velocity

Both iodine-131 and bromine-82 were used ,one by one, as tracers for determination of filtration velocity in the well. The tracer was injected in the entire column of the borehole by a special injection assembly. Uniform mixing of the tracer was ensured by moving the dead weight of the injection assembly.

Measurement of dilution rate was carried out at 8.5 m depth, ie. at the middle of the perforated filter (see Fig.1). The details of the construction of the borehole, ie. radiusof the filter tube,gravel pack from which the value of α was determined are shown in Figure 1. The values of permeability of the filter tube k_1, gravel pack k_2 and of the formation k_3 have been reported to be as following(IPT,1979);

$$k_1 = 0.5 \quad cm/s$$
$$k_2 = 0.5 \quad cm/s$$
$$k_3 = 8.5x10^{-4} \quad cm/s$$

The value of α calculated by means of equation(6) from the available data of $r_1, r_2, r_3, k_1, k_2, k_3$ is 2.94.

Normally, when the condition $k_1 \gg k_2 \gg 10k_3$ is satisfied, α can be computed from the data of r_1, r_2 and r_3 alone. Such computations in graphical form are available in literature (DROST et al; 1968 ; HALEVY et al; 1967). From these graphs a value of 2.7 for α has been derived and is used in the present investigations.

Since the data of radii of the borehole is more reliable than the values of k_1, k_2 and k_3 determined in the laboratory conditions, the value of α computed graphically may be taken as more representative.

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 Fig.3 and Fig.4 respectively.

The dilution curves have been obtained after applying the correction regarding the decay of the isotopes 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 respective figures.

Determination of direction of ground water

For deermining direction of flow, ^{51}Cr as chromium chloride was used as adsorbable tracer. 1 ml of 1mCi/ml solution of the tracer was injected at 8.5 m depth. 1 ml of the tracer was taken in 3 mm diameter polyethylene tube by a micro metering pump. The tube was lowered upto the point of injection along with a centering device which was supported by a nylon rope. The pump was operated at a very low 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(Fig.5)was lowered to the point of injection by means of square rods made of alumunium. 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 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 Fig.6 was obtained.

DISCUSSION OF RESULTS

The filtration velocity of 4.6 cm/d obtained in the area of investigation is quite low. This indicates that ground water gradient in the area is very small. Earlier investigations (IPT,1976) indicate a value of 1.3×10^{-3} for the hydraulic gradient which can be considered as an average for the area of investigation. Permeability of the aquifer calculated from the relation

$$v_f = k_3 \cdot I$$

comes out to be 3.2×10^{-3} cm/s. The permeability of the aquifer as determined by conventional pumping tests carried out in the past is reported to be 8.5×10^{-4} cm/s (IPT,1979). Thus, there is quite good agreement between the results obtained by tracer dilution method and the pumping test method.

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

The direction of ground water at the point of measurement is towards the complex of IPT. This is also in agreement with the general direction of flow in the region as reported earlier (IPT,1976).

Use of radioactive tracers, thus, offers a very good tool for determining ground water parameters.

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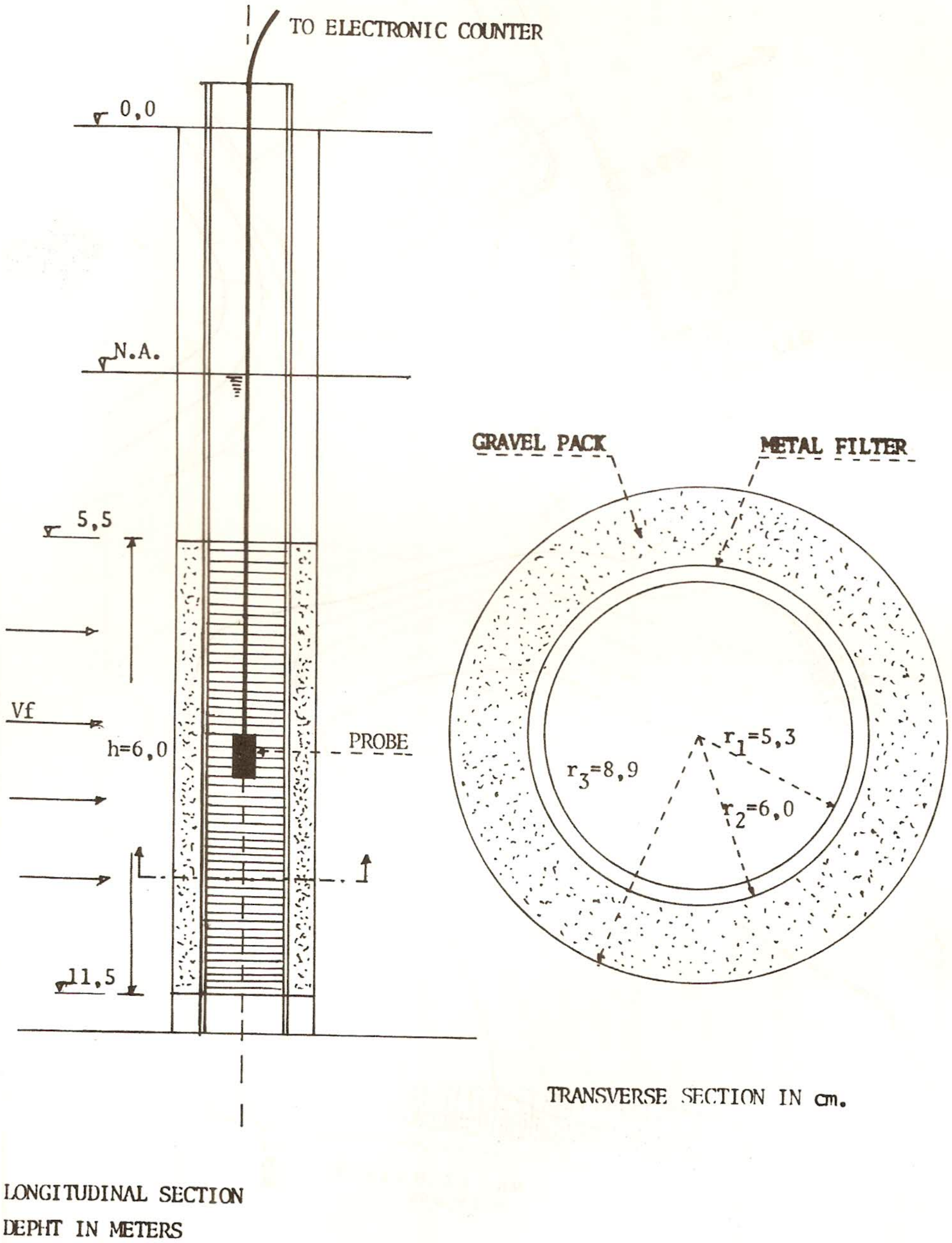


FIGURE 1 - DETAILS OF BOREHOLE-CONSTRUCTION AND INJECTION OF RADIOACTIVE TRACER

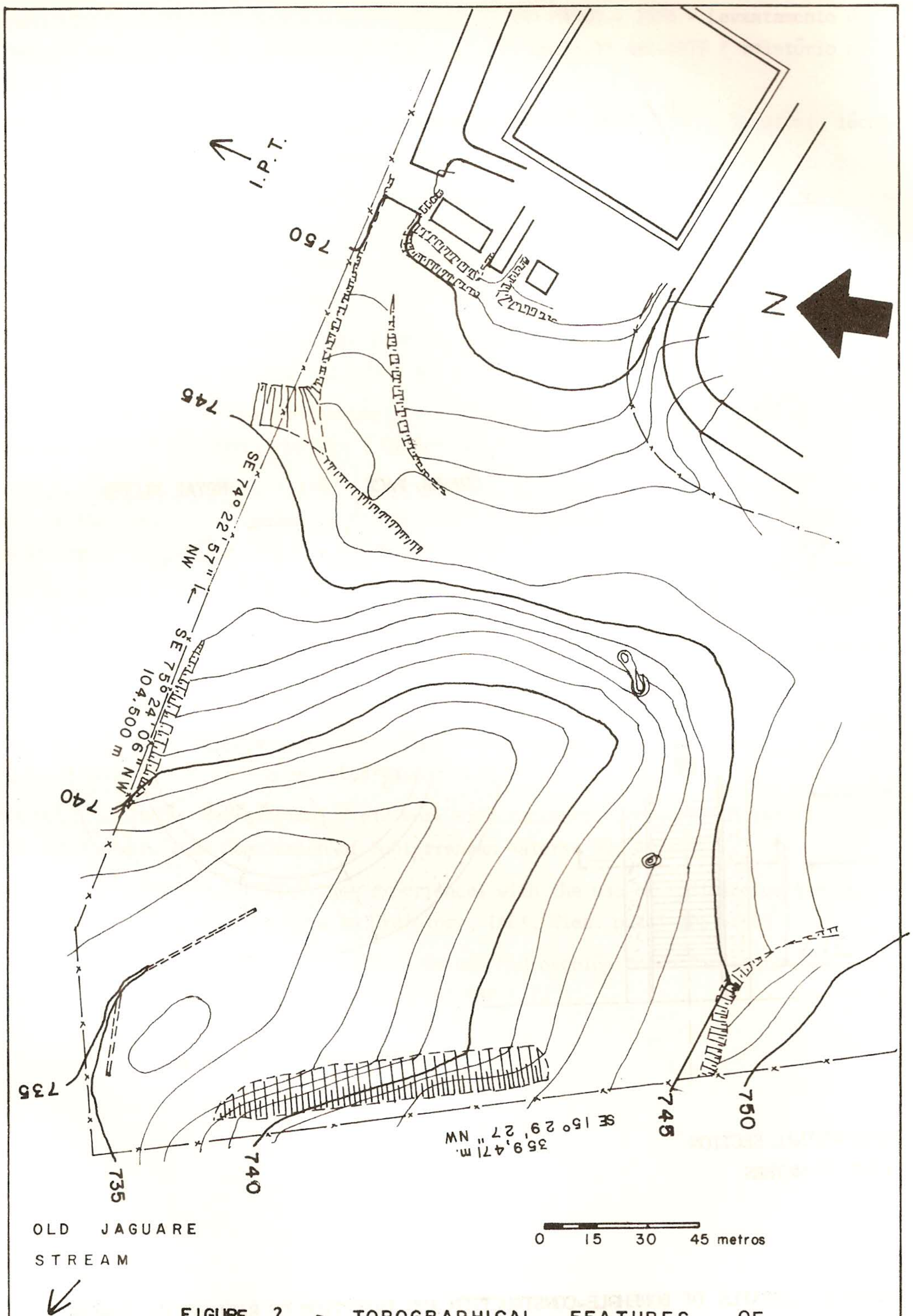


FIGURE 2 - TOPOGRAPHICAL FEATURES OF THE RADIOACTIVE WASTE DISPOSAL SITE, I.P.E.N.

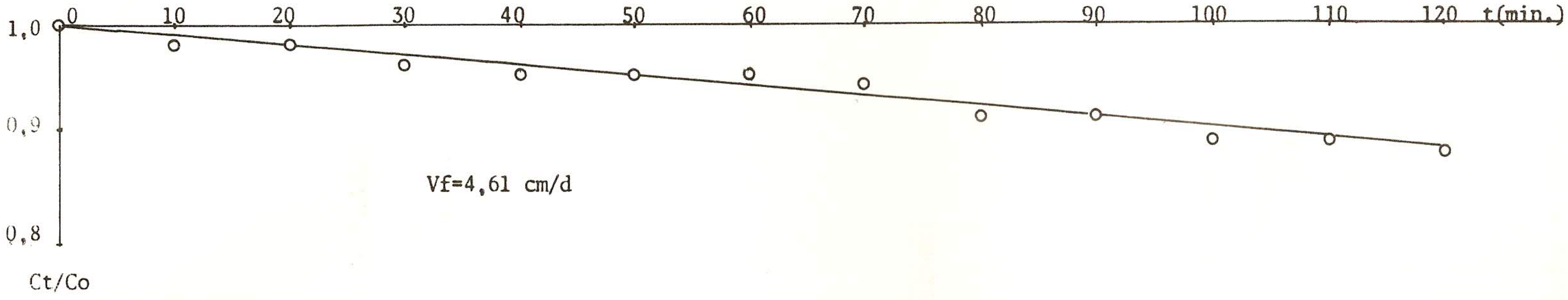


FIGURE 3 - DETERMINATION OF VELOCITY OF GROUND WATER BY IODINE-131 AS TRACER

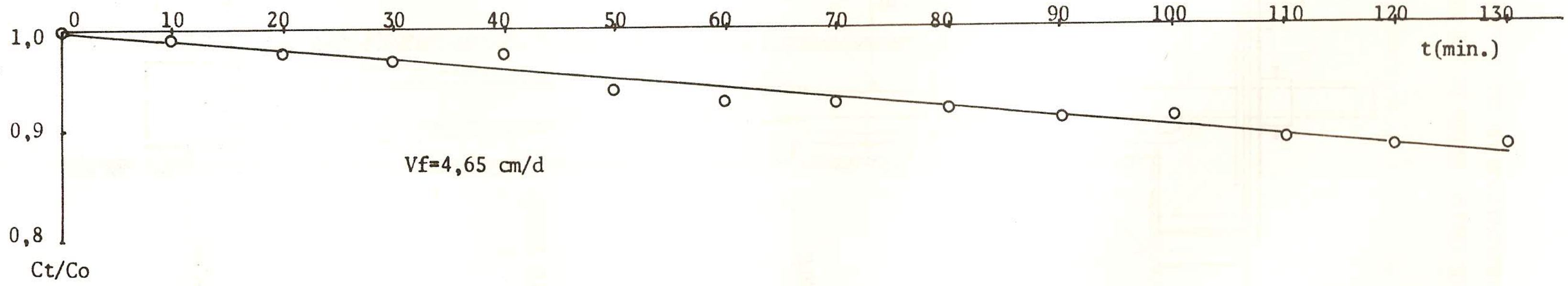
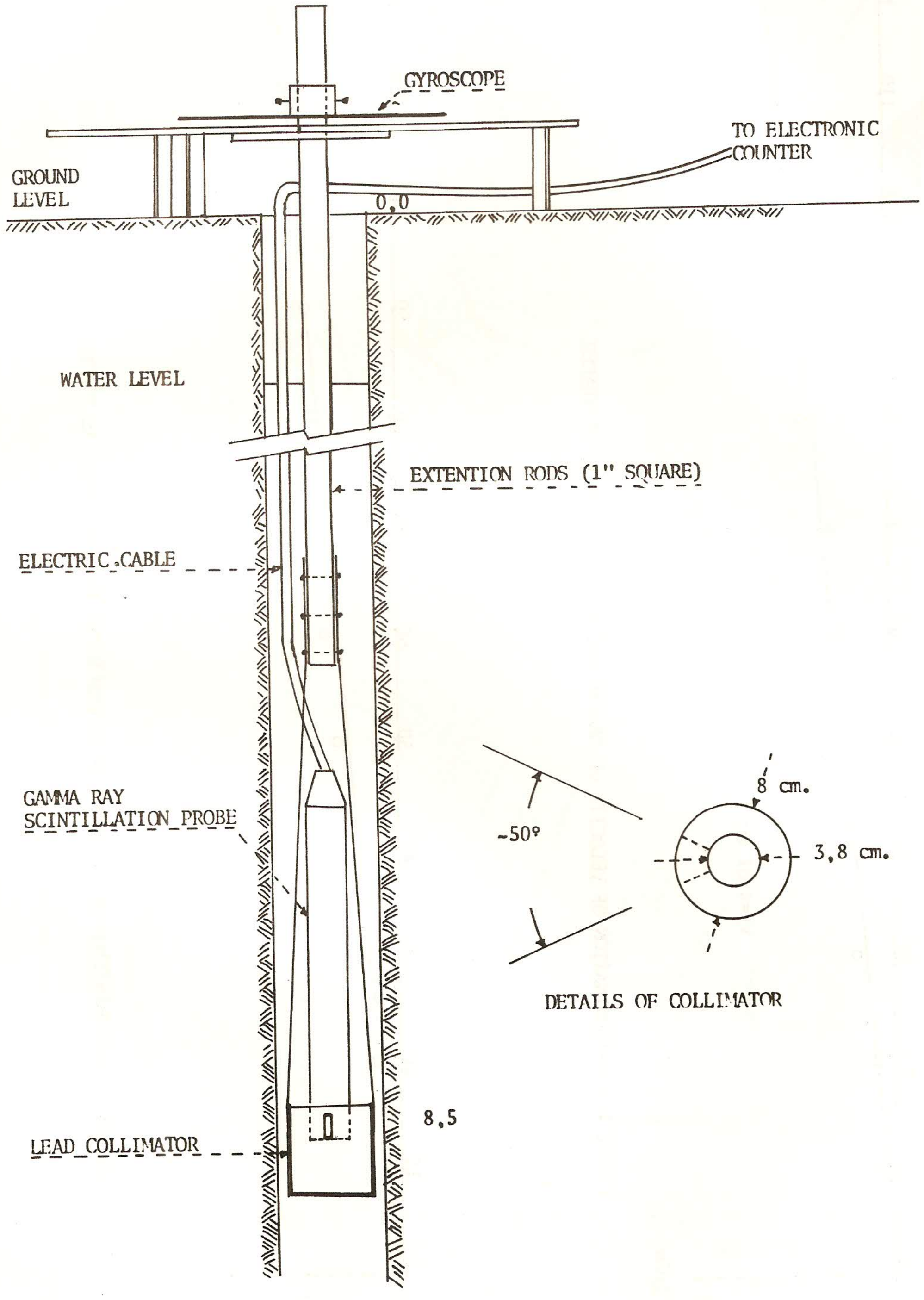
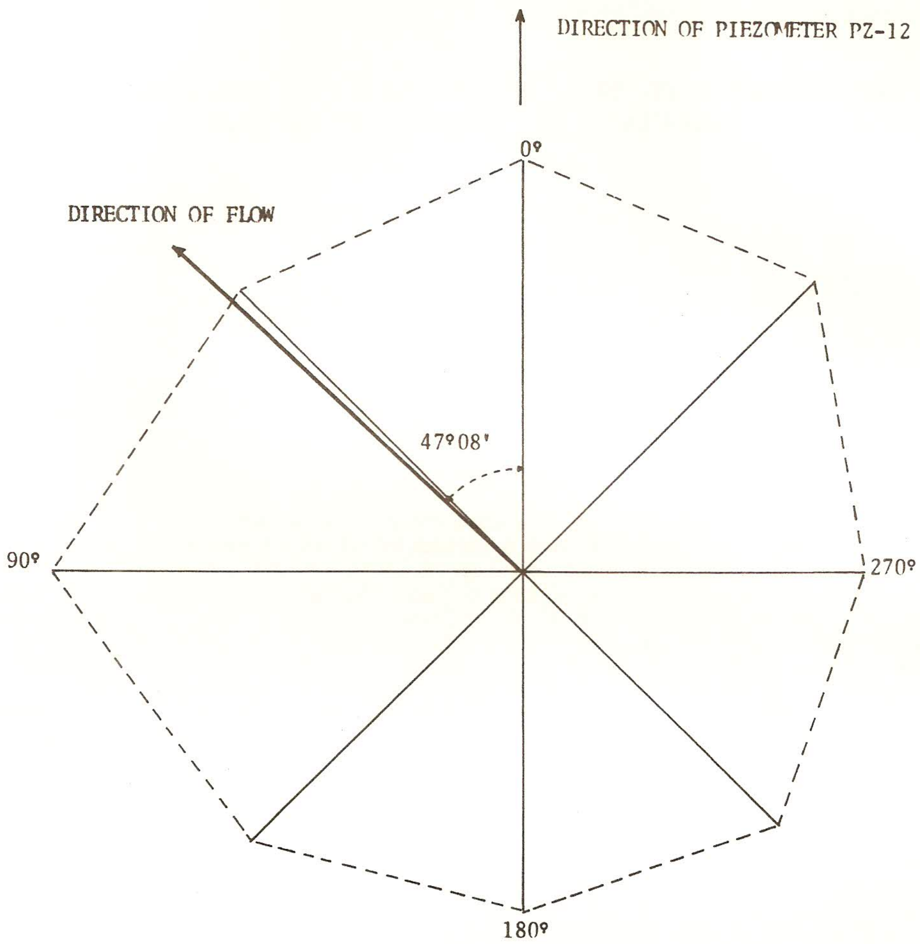


FIGURE 4 - DETERMINATION OF VELOCITY OF GROUND WATER BY BROMINE-82 AS TRACER

FIGURE 5 - DESCRIPTION OF THE SYSTEM USED FOR DETERMINATION OF DIRECTION OF FLOW OF GROUND WATER IN THE WELL





DIAMETER OF WELL: 4"

FIGURE 6 - DIRECTION OF GROUND WATER IN THE WELL