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ABSTRACT

This report describes the laboratory and field work connected with the study of the fate of radionuclides already buried at the burial ground of the AAEC Research Establishment at Lucas Heights. The study complements and expands investigations made before the burial ground was established.

The very slow movement of radioactivity from the buried waste is confirmed by environmental monitoring. The ion exchange capacity of the soil and the minimal groundwater velocity both contribute to the retention of radioactivity in the area.

A simple model is developed to demonstrate the capacity of the burial area for radioactive waste.

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RADIOACTIVE WASTE DISPOSAL; UNDERGROUND DISPOSAL; RADIONUCLIDE MIGRATION; AAEC

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1. INTRODUCTION

The Research Establishment of the Australian Atomic Energy Commission at Lucas Heights is located 30 km south-west of Sydney, New South Wales. The site has an area of 68 hectares which accommodates two reactors used for radioisotope production and research, and approximately seventy buildings. From 1960 until 1968, an area of four hectares of land, 1.6 km north of the Research Establishment, situated in the Little Forest area, was used as a burial ground for low and medium level radioactive solid waste (Figure 1).

Because of uncertainty that developed regarding potential land usage in the immediate vicinity, burial ceased. Up to the present, no radioactivity (apart from that caused by tritium) has been detected in groundwater outside the fenced burial ground which may be attributed to the buried waste.

This study assesses the fate of the radionuclides already contained in the burial ground and covers hydrological and chemical aspects of the movement of radioactivity through soil.

2. THE BURIED WASTE

The buried waste consisted of two main components:

1. Dried sludge, arising from the low level sludge blanket clarifier of the effluent treatment plant at Lucas Heights, which was essentially hydrated aluminium oxide. This constituted approximately 10 per cent of the total waste volume and was contained in 200-litre steel drums with a maximum surface dose rate of 10 mrem h^{-1}.

2. Laboratory trash and unserviceable equipment, including paper, glassware, damaged laboratory equipment, metal turnings, plastic and rubber tubing, etc. Although the laboratory trash was more diversified than the sludge, it contained similar identified emitters. These wastes were packed in 42-litre kraft paper bags which are bitumen impregnated and sisal fibre supported, or fibre board drums. Surface dose rates were usually well below the set limit of 200 mrem h^{-1}. Larger items of contaminated equipment such as ventilation ducting, filters, glove boxes and general laboratory apparatus, are usually wrapped in plastic sheeting or packed in boxes to prevent contamination spread (during transport) before burial.

The waste contained less than the following amounts of radioactivity per container:

0.5 mCi of Group I* radionuclides (including 10 mg ^{239}Pu)

or

20 mCi of Group II* radionuclides (including 2 g ^{233}U and mixed fission products)

or

1 Ci of radionuclides of Group III* and higher groups (excluding natural U, ^{235}U and natural Th)

or

150 g of soluble natural U, depleted U or natural Th

or

2 kg of insoluble natural U, depleted U or natural Th

or

10 g of ^{235}U

or

5 g of dispersible beryllium in any form.

Altogether about 47 600 packages, total volume 1675 m^3, were buried in 77 trenches. More details of the composition of the waste are given in Appendix A.

2.1 Characteristics of Solar Evaporated Sludge

The radioactive components of the sludge had low specific activities; γ-spectrometry has identified ^{137}Cs (1.9 nCi g^{-1}), ^{60}Co (2.2 nCi g^{-1}) and ^{54}Mn (0.4 nCi g^{-1}). Using the assumption that their relative abundances were similar to those found in the untreated waste streams from a PWR, Table 1 gives the expected $\beta\gamma$ radioactive content (based on average over all USA plants [USAEC 1973]). It shows that the nuclides which have the most significance by ingestion through the food chain are ^{90}Sr, ^{137}Cs, ^{134}Cs and ^{60}Co.

As the evaporated sludge was not completely dried (water content ~ 15 per cent) the presence of entrained tritium is possible. Maximum discharge figures of tritium in effluent which has been in contact with the sludge [B.G. Stewart, AAEC private communication 1976] suggest that a concentration no greater than 9 μCi tritium/drum could be expected from entrainment.

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* See Appendix B.

2.2 Leaching of Solar Evaporated Sludge

A close study of the sludge showed that it consisted of two components black and grey in colour. The black component contained 3.8 nCi g^{-1} ^{60}Co and 0.2 nCi g^{-1} ^{137}Cs, and the grey component contained 0.8 nCi g^{-1} ^{60}Co and 2.0 nCi g^{-1} ^{137}Cs. Desorption studies on 50 g samples (0.25-0.5 mm) which were shaken vigorously for 30 minutes with 50 mℓ of borehole water, indicated that the total radioactivity was leached more effectively from the black component (Tables 2 & 3). The results also suggest that ^{137}Cs was held more strongly on the grey component and this probably explains the unexpectedly low removal of ^{137}Cs from sludge in the drum experiment described later.

Shake tests performed on a mixture of black and grey components, containing approximately 1.5 nCi g^{-1} each of ^{60}Co and ^{137}Cs, confirmed that ^{60}Co was more effectively desorbed than ^{137}Cs (Table 4).

The sludge drum experiment was devised to simulate the flushing of buried sludge with rain and groundwater, and initially consisted of the percolation of 5 litres of tap water (20 mm rain) daily for 10 days through a drum of sludge containing 300 μCi ^{137}Cs, 350 μCi ^{60}Co and 60 μCi ^{54}Mn, and the collection of leachate through an outlet tube at the bottom of the drum. After the equivalent of 200 mm of rain was passed through, the sludge was totally immersed in water (approximately 75 litres).

The results by γ-spectrometry (Table 5) showed that only 0.04 per cent of the total activity of ^{60}Co, ^{137}Cs and ^{54}Mn was leached by percolation. Total immersion over a period of sixteen months with seven batches of water, extracted a further 0.3 per cent ^{137}Cs, 0.5 per cent ^{60}Co and 1.4 per cent ^{54}Mn (Table 6). The leaching data show that the desorption of activity from the sludge under conditions similar to burial is very slow. The total immersion of the sludge in water was not unlike burial conditions, as hydrographs subsequently obtained (Section 3.4) show that the buried waste is almost continuously immersed in groundwater.

Gas proportional counting analysis of the leachate for gross α and gross β activity confirmed the slow desorption rate of activity. After a total of 537 litres of water had been in contact with the sludge over 16 months (Figures 2 and 3), a total of 0.2 μCi gross α-activity and 3.0 μCi gross β-activity was desorbed. The mean concentration of β-activity was 5 nCi $ℓ^{-1}$. (A figure of 10 nCi $ℓ^{-1}$ was obtained in the laboratory

by stirring crushed sludge (1 mm) with water for 48 hours [P.S. Bull, private communication].)

The leaching experiments show that leaching of radioactivity from sludge by groundwater is slow and, in one year, less than 0.5 per cent of the ^{137}Cs and ^{60}Co was extracted from a drum of sludge. By way of comparison a 'typical' drum of trash was leached under similar conditions to the sludge. The leach solution contained less activity than sludge leachate, confirming that dried sludge is the major waste source.

It may be possible for water containing material in the process of biological degradation to come into contact with buried sludge. Leachate (200 mℓ) obtained from a nearby tip was contacted under anaerobic conditions with 50 g sludge. In one month, leachate removed more ^{60}Co (10 per cent) and ^{137}Cs (4 per cent) than groundwater. After two months, only 0.8 per cent each of ^{60}Co and ^{137}Cs was found in a soluble form which finally reduced to 0.4 per cent of ^{60}Co and 0.6 per cent of ^{137}Cs.

After five months, during which bacterial growth and precipitation of a fine black solid occurred, the pH increased from 6.0 to 7.6. The inhibiting effect on desorption which was concomitant with bacterial growth may account for the 'plateau' observed in the leaching data obtained from the sludge drum experiment (Figures 2 and 3).

3. THE BURIAL GROUND

The burial ground consists of a rectangular enclosure 349 m long and 116 m wide. Two areas of trenches in the north-east located in the highest section of the burial ground, 132-133 m above sea level, contain the buried waste. The trenches are nominally 25 m long, 0.6 m wide and 3 m deep and are spaced 2.7 m apart. The waste is buried under 1 m of consolidated overburden.

Ten 15 cm diameter boreholes (BH1, BH2 ... BH6, OS1, OS2, OS3, BH10) are located along the western and eastern fences and five boreholes (A-E) are located outside the northern fence (Figure 4). The depths of the boreholes are given in Table 7.

A shale quarry, 8 m deep, is located along the western face of the burial ground about 20 m from the fence. The direction of surface drainage from the burial ground is towards Mill Creek in the north and Barden's Creek in the east (Figure 1) which eventually flow into Georges River, 7 km north of the burial ground. There is no permanent habitation in the surrounding Little Forest area (approximately 80 ha).

3.1 Geology

The dominant rock formation outcropping on the Woronora Plateau is Hawkesbury Sandstone which extends to a depth of approximately 200 m, and is of Triassic age, with overlying remnants of basalt and Ashfield Shale of the Wianamatta Group. The Ashfield Shale consists of siltstone which is generally deeply weathered to a depth of about 6 m, resulting in clay. Some fresh siltstone is preserved at the base as shale.

Clay mineral identification [Slansky 1975] by X-ray powder diffraction analysis of four samples (F1-F4) of argillaceous material, obtained from a face of a trench dug in the north-west section of the burial ground, confirmed a preponderance of kaolinite (Table 8). A fifth sample (F5) was obtained from the sandstone profile at 9 m, from cores drilled east of the burial ground.

The cation exchange capacities of the five samples ranged between 4.5 to 9.0 x 10^{-2} meq g^{-1} soil as determined by a modified technique described by Bower and Truog [1940]. The modifications consisted of substituting a calcium chloride solution for manganese chloride at the saturation stage, and using atomic absorption spectroscopy to analyse the calcium.

In clays of the 1:1 type (kaolinite), the layers of silica and alumina are closely spaced, restricting the entry of cations into the lattice. The mechanism is by replacement of H^+ from the ionisation of the OH^- ion or direct sorption at exposed crystal edges. The sorption is enhanced by a decrease in ion size or, in the case of the replacement of H^+, by an increased pH.

3.2 Climate

The climatic characteristics at the burial ground are like those of station No. 066078 at Lucas Heights. Figure 5 gives the monthly mean maximum, mean minimum temperature and mean monthly rainfall averaged between 1962 and 1974 at Lucas Heights. The total annual rainfall averages 1061 mm. The number of rain days over the same period (1962-74) confirms that precipitation is greater in spring and early summer.

3.3 Hydrology

The burial ground is elevated about 130 m above sea level on a perched aquifer (i.e. isolated body) that exists above the Woronora Valley as a result of the presence of a shale lens with low permeability.

Groundwater losses are mainly from evapotranspiration and seepage. The shale bed is believed to be relatively impermeable and vertical leakage should be negligible.

Observations after heavy precipitation indicate that the run-off dilutes any soluble activity that may have come to the surface. Run-off water from the burial area collects in a drain near OS1 (Figure 4) which eventually flows in Barden's Creek. Run-off also occurs to a lesser extent from the north of the burial area towards BH10.

3.4 Groundwater Movement

Hydrographs compiled between June and December 1974 (Figures 6-9) show the recharge and discharge characteristics of the boreholes. The difference between maximum and minimum water levels is greatest in the western section of the burial area near BH2 and 3, indicating that there is a faster discharge from that area (probably flowing beneath the floor of the adjacent quarry).

The hydrographs also show that precipitation of about 150 mm produces an average rise in groundwater level of 120 cm over the burial ground, which is compatible with a porosity of 10 per cent and a run-off figure of approximately 20 per cent. This suggests that recharge water in the burial area is from precipitation over the burial area.

Standing water levels obtained over wet and dry periods show the general direction of groundwater movement, the flow always being at right angles to the contours (Figures 10-14). It is apparent that there is flow to the north and west because of the gradients that exist. There is also some flow to the east because of the higher permeabilities found in the area (Table 9). Flow to the south-west from the burial area is negligible.

Hydrographs of boreholes A-E show small variations in groundwater level, probably as a result of the low permeability of the soil in the area (Section 3.5).

Appendix C lists the headings under which information is required for land burial as indicated by a 1974 United States Geological Survey Report presented by the Comptroller General of the USA [ERDA 1976]. Although some of the headings are not relevant to the Little Forest area, the report illustrates that further hydrological data must be obtained for a comprehensive appraisal of the burial ground.

(i) Groundwater velocity measurements

The point dilution technique [Inoue 1967] was used for velocity measurements. The groundwater velocity $\bar{v}$ is calculated from the change in the concentration of the tracer injected into a borehole and given by

$$\bar{v} = \frac{\pi d \, \ell n \, \frac{co}{c}}{8t}$$

where d = diameter of the well

co = original activity

c = activity after time t.

Iodine-131 tracer was selected and preliminary shake-up tests with soil fractions F1-F4 showed no sorption of activity on F2-F4. After 5 days F1 commenced to absorb ^{131}I and, within 9 days, about 80 per cent of the tracer was absorbed. It was concluded that organic matter present in the top soil had adsorbed the ^{131}I. Groundwater velocity measurements were performed when water levels were below the layer of top soil, thereby precluding the possibility of soil adsorption. At borehole OS3, Rhodamine B dye was used as a tracer before ^{131}I and an identical velocity figure was obtained.

Table 10 shows that the velocities do not exceed 2.0 cm day^{-1} for the boreholes studied.

(ii) Groundwater direction

A number of techniques are available for the determination of groundwater direction with radioactive tracers. Mairhofer [1963] and Borowczyk *et al.* [1965] used a method of detecting the maximum movement of radioactivity within a borehole either with a collimated probe or a radial array of detectors. Wurzel and Ward [1965] eliminated the need for *in situ* measurements by lowering into the borehole a perforated metal screen on which adsorption takes place. The screen is later cut into segments and counted in the laboratory. The activity is assumed to be proportional to the flow.

In our preliminary work, ^{198}Au was used as a tracer for direction studies. Metallic gold was irradiated, then dissolved in aqua regia and adjusted to pH 5. The solution was mixed with water in a borehole by means of a pump and allowed to stand for a few days. A collimated probe with a 4 cm slit was lowered into the borehole and the activity measured. The highest activity would be expected downstream from the water flow. The results were inconclusive (Figures 15-16) and conflict with those obtained with a float [D. Roman, AAEC private communication 1976]. From

Figure 15 the general direction of water movement in BH2 could be south/south-west, whereas float measurements have indicated the groundwater direction to be to the south-east. It has also been observed from float measurements that the water direction alters at various depths.

Figure 16 indicates that at BH10 the groundwater flow is to the west but groundwater contours (Figures 10-14) suggest the movement of water is to the north.

Table 11 shows the direction of groundwater movement obtained by three different methods at different times at BH2, each method giving a different result. It is obvious that there is a need for further investigations into a suitable method for measuring groundwater direction to allow for a more accurate prediction of the movement of contamination from buried radioactivity.

3.5 Chemistry of Groundwater

Averaged results of the chemical analysis of groundwater obtained from fifteen boreholes in eleven months (Table 12) show that there is a marked difference in ionic concentration of the borewater inside and outside the burial ground. Boreholes A-E at the north are situated in a forest area, which probably explains the higher ionic concentration due to transpiration. It could also be possible that these boreholes are associated with a different aquifer system which includes borehole BH10 (inside the burial ground) and which has a similar concentration of ions. The high concentration of Na^+ found in the groundwater in this area causes swelling in the ion exchange phase of the clay which, in turn, adversely affects the permeability of the soil. The low discharge of water (Figure 9) in the region is probably due to this depressed permeability.

Table 13 lists the average pH over nine months of the groundwater in the boreholes, the values ranging between pH 4-8.

3.6 Chemistry of the Soil

3.6.1 Permeability using single well pump-down tests

Permeabilities were determined *in situ* by pump-down tests on single holes. Assuming homogeneous strata at the borehole depths, the empirical equation of Ernst [Luthin 1957] provides a value for k (permeability or hydraulic conductivity) to within ± 20 per cent. Ernst pointed out that the measurements should be completed before 25 per cent of the volume of water removed from the borehole has flowed back into it.

$$k = \frac{4000}{(20+\frac{d}{a})(2-\frac{y}{d})} \quad \frac{a}{y} \quad \frac{\Delta y}{\Delta t} \quad ,$$

where Δy = rise of water surface in borehole during the time interval Δt;

d = depth of hole below water table;

y = distance from static water table to elevation of water in the hole; and

a = radius of hole.

k is expressed in metres d^{-1}. All other quantities are in centimetres or in seconds.

The permeabilities range between 0.001 to 0.13 m day^{-1} (Table 9), typical of clays classified as 'poor aquifers'.

3.6.2 Distribution coefficients of nuclides in the soil

The distribution coefficient of an element between a solid and aqueous phase is given by

$$K_d = \frac{C_s}{C_a}$$

where C_s = the equilibrium concentration sorbed in the solid phase in m mol g^{-1}; and

C_a = the equilibrium concentration in the solution phase in m mol $m\ell^{-1}$.

K_d has the units $m\ell\ g^{-1}$ and can be measured by batch or column methods.

Measurements of radioactivity via radioactive tracers in the original and final solutions provided the data on the distribution coefficients by the batch method.

It was shown by Routson and Serne [1972] with batch experiments that prewashes with influent solution are essential before measuring the K_d of strontium because competition from calcium results in low K_d values.

Distribution coefficients were determined with borehole waters of different ionic concentrations and pH.

Table 14 shows the effect on the K_d values of ^{85}Sr and ^{137}Cs of varying solid/liquid ratios. From these a ratio of 0.05 was selected because it is the lowest ratio compatible for K_d values of both ^{137}Cs and ^{85}Sr and gives the accuracy required for mass balance calculations. There should be an excess of the solution phase, otherwise preferential extraction of Ca^{2+} occurs, resulting in depressed values of K_d for other ions.

The distribution coefficients were determined for uranium, thorium, strontium, caesium and cobalt on 1 g soil samples (0.25-0.5 mm size) after pre-equilibration with three 10 mℓ portions of influent solution (filtered borehole water). The soil was washed with alcohol, dried at 80°C and subsequently contacted with 20 mℓ filtered borehole water containing a tracer of the particular isotope whose K_d was sought. Contact time was terminated when consecutive results were similar. Caesium reached equilibrium rapidly in one hour but cobalt took 96 hours to equilibrate with top soil and 16 hours with shale. All other nuclides were contacted to equilibrium in not less than 96 hours.

Tables 15 and 16 give the distribution coefficients for the isotopes listed earlier, using borehole water from BH10 and BHB respectively. The higher concentration of calcium in BHB water generally resulted in lower distribution coefficients for all the isotopes.

The minimum distribution coefficients of the more important nuclides, obtained over the four soil fractions and two borehole waters are cobalt 2, strontium 1, caesium 1600 $m\ell\ g^{-1}$.

3.6.3 The effect of pH on distribution coefficients

The distribution coefficients of all the nuclides decrease at higher H^+ concentrations, and at pH 2 there is a marked drop in K_d.

At higher pH, OH^- is released by ionisation causing replacement of H^+ which results in higher K_d values (Tables 17 and 18).

The increased capacity for adsorption at higher pH may provide a useful practical procedure for preventing the spread of contamination in soils by the addition of dilute alkali.

3.7 Environmental Monitoring

Regular environmental surveys of the burial ground and its environs are performed at six-monthly intervals [Dudaitis 1973, 1974; Davy & Dudaitis 1974, 1975]. Water, grass and vegetation are sampled for radioactivity. It is concluded from these reports that grasses take up more ^{60}Co than do acacia bushes. For example, samples of acacia taken from trenches 70-71 over the period 1970-73 showed 0.8 to 3.7 pCi ^{60}Co g^{-1} ash, whereas grass samples over the same period contained 6.1 to 8.0 pCi ^{60}Co g^{-1} ash.

Analysis for α-β activity at boreholes generally showed that higher readings for α-activity were found at borehole BHD ranging between 5-113 pCi ℓ^{-1}. Both α- and γ-spectrometry showed that the α-activity is from natural sources, e.g. traces of uranium and thorium in soil.

The highest β-level was detected at OS3 (106 pCi ℓ^{-1}) and includes that due to naturally occurring potassium-40 [Dudaitis 1973, 1974].

For the purpose of further monitoring, 23 (D1-D23) ~ 5 cm diameter holes were drilled using a Winkie GW-15 drill powered by a 10 hp two-stroke petrol motor. An AXT diamond coring bit and reamer coupled to a 1.8 m double tube core barrel was used in conjunction with A size 'Mag-Zirc' drill rods. The holes were cased with perforated hardened PVC tubes, 40 mm in diameter.

Core recovery was generally poor in the soft clay formation when drilling D1, D2 and D3 at distances of 33, 66 and 100 m, respectively, from the eastern fence of the burial ground. Cores were only obtained at about 6 m when the consolidated shale zone was penetrated. In all three holes, the sandstone profile was reached at 8.8 m after penetration of clay, leached shale and unweathered shale.

The remaining boreholes D4-D23 were drilled to 3 m (without core recovery) and cased. D17 on the north of the burial area near trench 77 was drilled at an angle of 30° so that it terminated approximately 1 m below trench 77. Boreholes D7-D23 were drilled around the immediate periphery of the burial area (Figure 4) to monitor the extent of dispersal of radioactivity from the trenches.

Water from boreholes D7-D23 showed the highest β- and α-activity near D9 and D10 (Table 19) and also the presence of ^{90}Sr and ^{60}Co (Table 20). At no time has the concentration of these nuclides approached discharge limits set by the NSW Radioactive Substances Regulations [1957] (^{90}Sr 3 nCi ℓ^{-1}; ^{60}Co 2 μCi ℓ^{-1}).

Tritium has been detected in most boreholes drilled around the burial area and its presence is attributed to some source buried in the past. The highest recorded level of 10.4 μCi ℓ^{-1} (Table 21) at D10 is only one-tenth of the discharge concentration permitted under the NSW Radioactive Substances Act.

Tritium measurements on run-off water at OS1 which originates from D10, D11 and D12 after precipitation, average about 3 nCi ℓ^{-1} which is about 1000 times lower than the mean concentration found at these boreholes.

Water from boreholes D7, D8 and D9 flows towards boreholes A-E both as sub-surface and run-off. The typical tritium concentration at D7-D9 is about 3 μCi ℓ^{-1} and at A-E about 3 nCi ℓ^{-1} (a dilution of about 1000). This dilution is probably due to seepage to the surface being

diluted with run-off water. Sub-surface dilution is expected to be considerably less.

Soil samples taken near D9 have shown levels of up to 33.9 pCi g^{-1} ^{60}Co and a study of the concentration configuration suggests that the ^{60}Co disperses from trench 71 on the west of D9. It is expected from the K_d of ^{60}Co obtained with different soil fractions that ^{60}Co in groundwater would preferentially adsorb onto surface soil.

Analyses of groundwater taken from 1 m below trench 77 at D17 (angle hole) and D18, an adjacent hole, showed only 7 pCi ℓ^{-1} ^{60}Co in the former and no radioactivity in the latter. This does not suggest that the contamination envelope has spread preferentially in the vertical direction because the sampling distances are not comparable. D18 would have to be 1 m from trench 77 instead of nearly 3 m.

Two holes, D15A and D18A were drilled adjacent to holes D15 and D18 respectively to approximately 6 m, to obtain water samples at greater depth. Gamma spectrometry on these samples showed the absence of radioactivity, as in the neighbouring wells. However tritium analysis showed a higher concentration in the deeper holes.

3.8 Concentration of Nuclides in Vegetation

Two 7 x 7 m fenced squares were cultivated as vegetable gardens. The 'active' plot was placed directly above trenches 76-77 which contained the most recently buried waste and also showed a 'hot spot' of 7000 cps (approximately twice the background level) at the north-west corner. The control plot was situated near the southern gate of the burial ground, approximately 250 m from the active plot.

Beans, field maize, sweet corn, potatoes, spinach and carrots were grown. The plants in the control plot showed much healthier growth due to higher quality soil and also due to their location, being less exposed to the wind.

The vegetables in the 'active' plot generally showed about the same level of radionuclides as the control vegetables except for ^{90}Sr for which the highest concentration factor, calculated as

$$\frac{\text{activity } g^{-1} \text{ ash in plant from active plot}}{\text{activity } g^{-1} \text{ ash in plant from control plot}}$$

of 1.5×10^3 was found in maize ash (Table 22). This is probably because the roots of the maize plant are more prolific and the plant was situated near the hot spot mentioned earlier.

Qualitative γ-spectrometry on a few active and control samples showed the presence of the fission products ^{95}Zr-^{95}Nb, ^{103}Ru and also ^{60}Co, the levels being slightly higher in the active vegetables.

4. DISCUSSION

4.1 Movement of Radionuclides

Both groundwater velocity and distribution coefficients are important parameters in determining the movement of a nuclide through soil which may be represented by [Inoue 1967]

$$\frac{Vo}{Vc} = 1 + \frac{1 - P}{P} \rho K_d$$

where Vo is the velocity of the groundwater,

Vc the velocity of the contaminant,

P the porosity of the soil, and

ρ the density of the soil.

The value of K_d depends on the concentration of ions in the groundwater and soil, the pH of the groundwater and the charge on the ion.

Using the values for K_d given in Section 3.6, and taking the groundwater velocity as 2 cm day^{-1}, porosity as 10 per cent and the soil density as 2, gives the effective velocities of the nuclides derived from the above equation as (cm day^{-1})

^{137}Cs	6.9×10^{-5}
^{90}Sr	0.1, assuming K_d of ^{90}Sr = K_d of ^{85}Sr,
^{60}Co	5×10^{-2}.

The distance of the eastern fence from the burial area is 8 m. Thus it would take the nuclides the following periods to reach the fence;

^{137}Cs	3.2×10^{4} years
^{90}Sr	22 years
^{60}Co	44 years,

which are confirmed by the absence of radioactivity outside the burial ground.

4.2 Limits on Buried Nuclides

The sludge leaching experiments described in Section 2.2 and Table 6 demonstrate that for conditions similar to those expected for buried wastes, 500 litres of water (7 drum volumes), in contact with the sludge, removed about 0.5 per cent ^{60}Co or ^{137}Cs over a period of 16 months.

The average groundwater velocity is about 1 cm day^{-1} (3.7 m $year^{-1}$)

and hydrographs show that the waste is almost continuously under water. The diameter of the buried drums is 60 cm, therefore the effective volume of water passing through the drum per year is 3.7/0.6, i.e. about 6 drum volumes. Thus, less than 1 per cent of each waste component will be released per year.

The data obtained from sludge leaching studies strongly suggest that sludge waste acts as if only a small percentage of the contained radioactivity can be removed by leaching.

The limit of buried waste is related to the concentration of activity that may be released at any time from the burial area, and it can safely be assumed that this concentration would at no time be greater than that obtained after the first year of leaching of the sludge.

In the following model, the restriction on burial is based on the limits set by the NSW Radioactive Substances Act [1957] together with expected behaviour of buried sludge.

The model uses the following annual figures:

Rainfall - 1220 mm (average over 100 years)

Run-off (20 per cent) - 240 mm

Evapotranspiration - 800 mm

Seepage - 180 mm

Area used for burial - 7442 m^2

Seepage volume through burial area - 1.3×10^6 ℓ.

The NSW Radioactive Substances Act 1957 (Regulations) para. 13 limits the discharge of radioactivity from any premises to not greater than 100 times the concentration in Schedule II. The limiting concentrations of radioactive seepage at the burial area would then be:

^{90}Sr 3×10^{-6} mCi ℓ^{-1}

^{60}Co 2×10^{-3} mCi ℓ^{-1}

^{137}Cs 7×10^{-4} mCi ℓ^{-1}.

In flowing from the burial area to the northern boundary, the groundwater is diluted by infiltrating rain falling on the undisturbed area. The ratio of these areas is 5, a conservative value taken as the dilution factor, which excludes the major dilution that is possible from soil adsorption. Therefore the concentrations of nuclides discharged may be increased to:

^{90}Sr	15 nCi ℓ^{-1}
^{60}Co	10 μCi ℓ^{-1}
^{137}Cs	3.5 μCi ℓ^{-1}.

Multiplying each by the annual seepage loss (1.3×10^6 ℓ) the allowable annual release quantities become:

^{90}Sr	19.5 mCi
^{60}Co	13 Ci
^{137}Cs	4.6 Ci.

If this is to be 1 per cent of the waste buried, the limit on burial becomes:

^{90}Sr	2 Ci
^{60}Co	1300 Ci
^{137}Cs	460 Ci.

These figures could be increased further, depending on the distribution coefficient of each isotope on to the soil. The limits are 400 times greater than the past and likely future waste arisings, (see Appendix A).

It is apparent from the model developed that the limitations imposed by the NSW Radioactive Substances Regulations have been met, but the more recent NSW Clean Waters Act [1970] has imposed more stringent limits on Class C (controlled waters). Both the Woronora and Georges Rivers have not yet been classified, but it is probable that they will be included under Class C and from Schedule 3 the maximum gross β-release into controlled waters is 300 pCi ℓ^{-1}.

It is not unreasonable to expect that an activity of 5 nCi ℓ^{-1} (being the mean concentration of the leachate) would be reduced to below the limit of 300 pCi ℓ^{-1} by the combined mechanisms of dilution and soil adsorption in movement from the burial area to the boundary of the property. Property owned by the AAEC includes Portions 251, 252 and 253 at Little Forest which provide a further 32 hectares approximately, to the north and east of the burial ground if required.

Environmental surveillance over the last ten years on borehole water taken from boreholes near the fence of the burial ground has shown no seepage of radioactivity outside the burial ground. One borehole OS3 situated at the north-east corner of the burial area, about 2 m from the eastern fence, has shown that the gross β-activity has not exceeded 106 pCi ℓ^{-1}. Borehole D9 drilled to 3 m at the centre of the burial area (Figure 4) has recently shown a maximum of 400 pCi ℓ^{-1}

(Table 20) but monitoring of the boreholes at the fence has confirmed that soil absorption has occurred.

4.3 Further Work

A comprehensive appraisal of the burial ground requires a deeper study of the hydrology of the area along the guide lines in Appendix C, together with definitive information on the rate and direction of groundwater movement at various points encompassing the burial area. It is not conclusive from analyses at the two boreholes, D15A and D18A that there is no preferential movement of radioactivity in a vertical direction and it would be desirable to drill further deep holes in the groundwater path.

Perched water tables are hydrologically complex. The existence of shale pits on two boundaries of the Little Forest area cause further complications by destroying any symmetry in the hydraulic gradients and by imposing on the groundwater flow regime a factor that depends on rainfall.

The acceptability of a burial site rests heavily on calculations for groundwater flow and waste/water interactions. For such calculations to be credible the systems must be simple. In general, this need for an area with simple hydrogeologic characteristics becomes a major constraint on the selection of a site for disposal of radioactive waste.

5. CONCLUSION

It is concluded that although no radioactivity has been detected outside the burial ground, the area is not an ideal location for the burial of radioactive waste because of the high water table that exists almost permanently. This is, however, compensated by the low specific activity of the material which has been buried in the past and which is anticipated for burial in the future if burial were resumed.

If burial of waste is resumed at the burial ground, it is essential that it does not take place west of the existing burial area as it would bring the source of activity too close to the quarry. Burial of waste south of the burial area would also be unwise as the area is low-lying and receives a high quantity of run-off water. Consequently, the future burial of radioactivity would be restricted to the north-east of the presently fenced burial ground, with a capacity of about 80 per cent of the present burial area. Further areas could, of course, be fenced and used if the necessity arose.

6. ACKNOWLEDGEMENTS

The authors wish to acknowledge, in particular, the assistance and expertise of Mr W.R. Ellis in groundwater tracer measurements, Mr D.E. Parsons for all γ-spectrometry analyses and Analytical Chemistry Section for the numerous analyses performed.

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TABLE 1

POSSIBLE RADIOACTIVE CONTENT PER 160 kg DRUM OF SLUDGE

(Excluding isotopes with half-life < 3 months)

Radionuclide	Half-life	Activity (μCi)
^{144}Ce	284 days	0.12
^{60}Co	5.25 years	352
^{134}Cs	2.05 years	340
^{137}Cs	30.0 years	304
^{55}Fe	2.6 years	158
^{59}Fe	45.6 days	3.6
^{54}Mn	303 days	64
^{147}Pm	2.62 years	0.01
^{90}Sr	27.7 years	0.04
^{127}Te	109 days	0.9
^{65}Zn	250 days	0.02

TABLE 2

LEACHING OF A 50 g BLACK COMPONENT ISOLATED FROM SLUDGE

Leachate	^{60}Co Extracted		^{137}Cs Extracted	
	pCi	%	pCi	%
1*	1280	0.68	115	1.3
2	850	0.45	80	0.9
3	650	0.35	60	0.7
4	680	0.36	90	1.0
5	330	0.18	40	0.4
6	320	0.17	60	0.7
7	410	0.22	50	0.6
8	290	0.16	50	0.6

** 100 mℓ used for leaching.*

TABLE 3

LEACHING OF A 50 g GREY COMPONENT ISOLATED FROM SLUDGE

Leachate	^{60}Co Extracted		^{137}Cs Extracted	
	pCi	%	pCi	%
1*	130	0.3	190	0.2
2	150	0.4	160	0.2
3	110	0.3	120	0.1
4	110	0.3	90	0.1
5	100	0.3	60	0.1
6	110	0.3	70	0.1

** 100 mℓ used for leaching.*

TABLE 4

LEACHING OF 50 g SLUDGE

Leachate	^{60}Co Extracted		^{137}Cs Extracted	
	pCi	%	pCi	%
1*	160	0.2	120	0.2
2	300	0.4	180	0.2
3	310	0.4	130	0.2
4	200	0.3	100	0.1
5	190	0.3	80	0.1
6	150	0.2	70	0.1
7	180	0.2	100	0.1
8 (24 h shake)	280	0.4	140	0.2

** 75 mℓ used for leaching.*

TABLE 5

LEACHING BY PERCOLATION OF WATER THROUGH A DRUM OF SLUDGE

(Containing 300 µCi ^{137}Cs, 350 µCi ^{60}Co, 60 µCi ^{54}Mn)

Equivalent of Rain Passed Through Drum (mm)	Progressive Total of Activity of Nuclide Released (nCi)		
	^{137}Cs	^{60}Co	^{54}Mn
20	2	2	0.6
40	5	3	1
60	8	5	2
80	15	10	4
100	23	16	6
120	31	20	7
140	51	30	12
160	70	38	16
180	92	48	21
200	119	60	26

TABLE 6

LEACHING BY TOTAL IMMERSION OF SLUDGE IN WATER

(Containing 300 µCi ^{137}Cs, 350 µCi ^{60}Co, 60 µCi ^{54}Mn)

Volume of Leachate Collected (ℓ)	Duration of Immersion	Progressive Total of Activity Leached (nCi)		
		^{137}Cs	^{60}Co	^{54}Mn
76	7 days	360	650	280
79	7 days	600	1170	540
80	9 days	710	1540	770
77	4 months	800	1700	870
71	7 months	870	1720	885
77	3 months	910	1725	898
77*	6 weeks	970	1730	905

** Borehole water from BH10 was used as leachant.*

TABLE 7

DEPTH OF BOREHOLES

Borehole	Depth (m)
BH 1	2.9
2	4.8
3	3.5
4	6.0
5	3.6
6	4.0
10	5.4
OS 1	2.2
2	3.5
3	3.8
BH A	11.6
B	8.3
C	9.4
D	11.6
E	11.6

TABLE 8

DESCRIPTION AND CATION EXCHANGE CAPACITY OF A SOIL PROFILE

Fraction	Sampling Depth (m)	Description	Composition	Cation Exchange Capacity meq/100 g
F1	0.0-0.5	Top soil	Kaolinite (> 50%) Mica, smectite (< 50%) Quartz	7.3
F2	0.5-1.0	Red-brown clay	Kaolinite (80%) Mixed-layer mica-smectite (20%) Quartz	9.0
F3	1.0-1.5	Greyish clay	Kaolinite (80%) Mixed-layer mica-smectite (20%) Quartz	7.1
F4	1.5-2.5	Weathered shale	Kaolinite (65%) Micaceous clay mineral (35%)	8.3
F5	9.0	Sandstone	Kaolinite (50%) Mixed-layer mica-smectite (50%)	4.5

TABLE 9

PERMEABILITY OF SOIL AT BOREHOLES

CALCULATED BY THE ERNST FORMULA

Borehole	Permeability (m day^{-1})	
	After rain	After drought
1	0.005	0.001
2	0.013	0.008
3	0.002	0.001
4	0.020	0.013
5	0.002	0.002
6	0.007	0.117*
OS1	0.060	0.035
OS2	0.012	0.003
OS3	0.096	0.052
10	0.030	0.025

** The high permeability figure may be due to the breakdown of soil structure near BH6 during drought conditions.*

TABLE 10

GROUNDWATER VELOCITY AT BOREHOLES DETERMINED

BY SINGLE HOLE TRACER TECHNIQUE

Borehole	Approx. Water Level (cm)	Level of Measurement (m)	Velocity (cm day^{-1})
OS3	80*	2	0.6†
OS3	115	2	0.2
BH10	70*	2	1.9
BH10	95	2	1.1
OS2	140	2	0.3
BH2	410	4.5	0.3

** Water level after precipitation*

† A velocity of 0.6 cm day^{-1} was also obtained with Rhodamine-B tracer.

TABLE 11

DIRECTION OF GROUNDWATER FLOW OBTAINED BY THREE DIFFERENT METHODS

Borehole	Tracer Method	Float Measurements	Water Contours
BH2	South/ south-west at 4 m	South-east at 2 m	West
BH3	-	Northerly at 2 m	West
BH10	West at 2 m	-	North

TABLE 12

AVERAGE* CONCENTRATIONS OF IONS IN BOREHOLE WATER (MARCH 1974 - JANUARY 1975)

(Concentrations in mg ℓ^{-1})

Figures in brackets indicate the range

Borehole	Sodium	Potassium	Calcium	Chloride	Sulphate
1	91 (62-200)	3 (2-6)	34 (17-62)	66 (15-192)	38 (9-160)
2	51 (40-65)	2 (1-4)	7 (3-11)	41 (27-53)	40 (10-75)
3	71 (46-120)	4 (3-5)	21 (6-37)	42 (21-92)	44 (13-110)
4	135 (28-520)	3 (1-6)	17 (5-44)	164 (36-980)	20 (9-55)
5	57 (27-110)	2 (1-2)	10 (4-19)	51 (21-163)	23 (13-46)
6	254 (28-480)	4 (2-8)	36 (8-87)	271 (20-767)	34 (12-65)
OS1	100 (49-210)	3 (2-5)	26 (11-38)	129 (75-323)	23 (7-90)
OS2	79 (68-100)	5 (3-6)	48 (28-98)	84 (60-121)	30 (12-80)
OS3	67 (45-100)	2 (1-2)	28 (15-38)	55 (23-121)	20 (12-55)
10	919 (780-1100)	16 (10-41)	18 (12-39)	1445 (1022-1976)	193 (112-300)
A	399 (73-810)	7 (4-18)	30 (16-54)	399 (56-1221)	35 (< 5-115)
B	1786 (1700-1900)	27 (23-41)	109 (65-150)	3397 (3245-3797)	127 (56-230)
C	1714 (1600-1900)	24 (19-30)	77 (25-110)	3032 (1961-3526)	110 (48-168)
D	740 (430-1300)	14 (10-29)	30 (21-50)	645 (454-793)	14 (5-20)
E	1116 (350-1900)	11 (3-25)	35 (14-76)	914 (61-2606)	97 (7-310)

** Averaged from the results of analysis of eleven monthly samples.*

TABLE 13

AVERAGE* pH OF GROUNDWATER FROM BOREHOLES

(MARCH 1974 - DECEMBER 1974)

Figures in brackets indicate the range

Borehole	pH
1	7.2 (5.1-8.2)
2	6.4 (5.6-7.5)
3	7.2 (6.5-7.9)
4	6.6 (6.1-7.6)
5	6.8 (6.5-7.4)
6	7.0 (6.2-7.9)
OS1	7.0 (6.2-8.0)
OS2	7.5 (7.1-8.2)
OS3	6.6 (6.2-7.5)
10	4.3 (3.7-5.9)
A	7.3 (6.7-7.8)
B	6.9 (6.3-8.0)
C	7.2 (6.5-8.1)
D	5.6 (4.4-6.9)
E	8.0 (6.9-8.6)

**Averaged from the pH of ten monthly samples.*

TABLE 14

THE DISTRIBUTION COEFFICIENTS OF ^{85}Sr AND ^{137}Cs AS A FUNCTION OF SOIL/SOLUTION RATIO

Concentrations of ions in mg ℓ^{-1} pH 7.2

Ca^{2+}	13	Al^{3+}	< 0.1
Na^{+}	840	Mg^{2+}	73
K^{+}	11	Cl^{-}	1200

Soil/soln	Distribution Coefficient (K_d)	
g/mℓ	^{137}Cs	^{85}Sr
1.0	-	2.4
0.4	-	8.0
0.2	1350	8.1
0.1	1540	8.2
0.07	2280	7.3
0.05	3710	8.1
0.025	3550	-
0.01	3230	-

TABLE 15

DISTRIBUTION COEFFICIENTS OF CATIONS URANIUM, THORIUM, ^{60}Co, ^{137}Cs, ^{85}Sr USING BOREHOLE WATER FROM BH10

Initial concentrations mg ℓ^{-1} pH 7.0

Ca^{2+}	13	Al^{3+}	< 0.1
Na^{+}	840	Mg^{2+}	73
K^{+}	11	Cl^{-}	1200

Solid/Liquid = 0.05

Soil Fraction	K_d mℓ g^{-1}				
	^{60}Co	^{137}Cs	^{85}Sr	U	Th
F1	38	3700	11	790	> 1000
F2	7	2100	9	34	176
F3	5	2500	7	26	85
F4	5	1600	7	71	81

TABLE 16

DISTRIBUTION COEFFICIENTS OF ^{60}Co, ^{137}Cs AND ^{85}Sr USING BOREHOLE WATER FROM BHB

Initial concentrations mg ℓ^{-1} pH 5.0

Ca^{2+}	170	Al^{3+}	0.7
Na^{+}	2000	Mg^{2+}	320
K^{+}	24	Cl^{-}	3370

Solid/Liquid = 0.05

Soil Fraction	K_d (mℓ g^{-1})		
	^{60}Co	^{137}Cs	^{85}Sr
F1	9	2900	1
F2	3	2100	2
F3	2	3600	1
F4	2	2700	1

TABLE 17

THE EFFECT OF pH ON THE DISTRIBUTION COEFFICIENTS OF URANIUM, STRONTIUM AND COBALT USING BH10 WATER

Influent solution (concentration in mg ℓ^{-1})

Ca^{2+}	13	Al^{3+}	< 0.1
Na^{+}	840	Mg^{2+}	73
K^{+}	11	Cl^{-}	1200

pH	K_d ^{85}Sr (mℓ g^{-1})		pH	K_d ^{60}Co (mℓ g^{-1})		pH	K_d Uranium (mℓ g^{-1})	
	F1	F4		F1	F4		F1	F4
2	0.8	2	2	2	2	2	130	3
4	9	6	4	19	6	4	570	60
7	10	7	5	17	6	6	670	70
9	12	9	9	32	18	9	680	70

TABLE 18

THE EFFECT OF pH ON THE DISTRIBUTION COEFFICIENT OF ^{85}Sr WITH BHB WATER

Initial concentrations in mg ℓ^{-1}

Ca^{2+}	170	Al^{3+}	0.7
Na^{+}	2000	Mg^{2+}	320
K^{+}	24	Cl^{-}	3370

pH	K_d ^{85}Sr (mℓ g^{-1})			
	F1	F2	F3	F4
2	0.4	0.6	0.4	0.7
5	1	2	1	1
7	2	3	2	2
9	2	3	2	2

TABLE 19

GROSS β- AND α-ACTIVITY IN BOREHOLES DRILLED AROUND THE BURIAL AREA

Borehole	Gross β pCi ℓ^{-1}		Gross α pCi ℓ^{-1}	
	Nov.-Dec. 1975	Feb. 1976	Nov.-Dec. 1975	Feb. 1976
D7	19	4	3	4
D8	6	7	2	6
D9	89	251	4	11
D10	9	27	5	7
D11	3	9	1	4
D12	5	3	< 0.5	3
D13	2	3	5	6
D14	5	5	3	6
D15	5	3	2	5
D18	-	4	-	4

TABLE 20

STRONTIUM-90 AND COBALT-60 IN BOREHOLE WATER

($pCi\ \ell^{-1}$)

Borehole	December 1975		February 1976		June 1976	
	^{90}Sr	^{60}Co	^{90}Sr	^{60}Co	^{90}Sr	^{60}Co
D7	5.1	Nil	0.1	Nil	0.2	Nil
D8	1.3	Nil	0.1	Nil	1.0	19
D9	20.1	114	54.7	350	71.0	250
D10	0.8	3	5.0	20	3.0	19
D11	0.3	Nil	1.1	Nil	0.7	6
D12	0.1	5	0.3	Nil	0.2	Nil
D13	0.1	Nil	0.1	Nil	0.2	Nil
D14	0.1	Nil	0.2	Nil	0.2	Nil
D15	0.2	Nil	-	Nil	0.2	Nil
D16	-	-	-	Nil	< 0.1	Nil
D17	-	-	-	Nil	9.2	7
D18	-	-	-	Nil	0.8	Nil
D19	-	-	-	Nil	0.6	Nil
D20	-	-	-	Nil	< 0.1	Nil
D21	-	-	-	Nil	< 0.1	Nil
D23	-	-	-	Nil	0.4	Nil
OS2W	0.2	Nil	0.3	Nil	0.4	Nil

TABLE 21

TRITIUM LEVELS IN BOREHOLES AROUND THE IMMEDIATE PERIPHERY OF THE BURIAL AREA

($\mu Ci\ \ell^{-1}$)

Borehole	Nov.-Dec. 1975 (Drought)	February 1976 (After rain)	May 1976	June 1976
D7	0.8	0.3	0.1	0.3
D8	5.4	4.0	6.4	3.5
D9	3.8	1.8	6.0	1.9
D10	10.4	5.7	4.4	2.6
D11	1.4	1.6	3.4	0.8
D12	2.4	0.8	0.6	0.3
D13	0.2	0.1	Nil	0.01
D14	2.3	1.3	0.4	0.07
D15	7.2	0.7	2.4	0.10
D16	-	-	0.06	0.02
D17	-	-	0.9	1.0
D18	-	0.9	0.8	0.7
D19	-	-	0.4	0.4
D20	-	-	2.0	1.2
D21	-	-	0.6	0.6
D23	-	-	0.4	0.3

TABLE 22

CONCENTRATION OF NUCLIDES IN ASH OF VEGETABLES GROWN IN AN 'ACTIVE' AND A 'CONTROL' GARDEN (JANUARY 1975)

Vegetable	^{90}Sr pCi/g Ash		Uranium µg/g Ash		^{226}Ra pCi/g Ash	
	Active	Control	Active	Control	Active	Control
Beans	19	~ 2	0.5	1.2	0.7	0.8
Carrots	2.4	1.2	0.8	0.8	0.5	0.9
Sweet Corn	0.7	0.4	0.6	0.9	0.3	0.2
Potato	1.0	0.2	0.3	0.3	0.6	0.2
Spinach	3.4	1.3	0.4	0.6	0.4	0.3
Maize	147	0.1	0.4	0.1	0.5	0.1

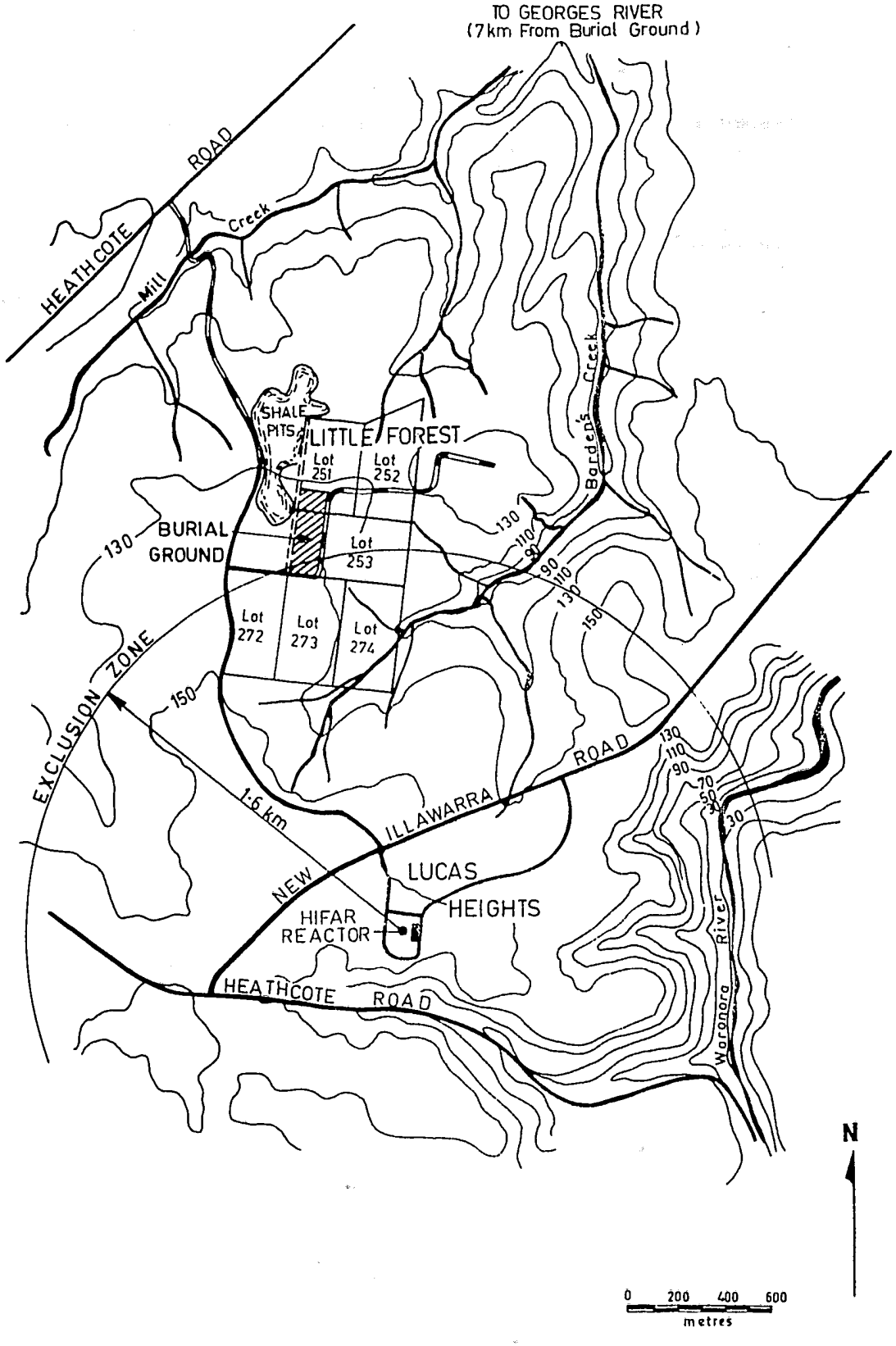

FIGURE 1. LOCATION OF LITTLE FOREST BURIAL GROUND

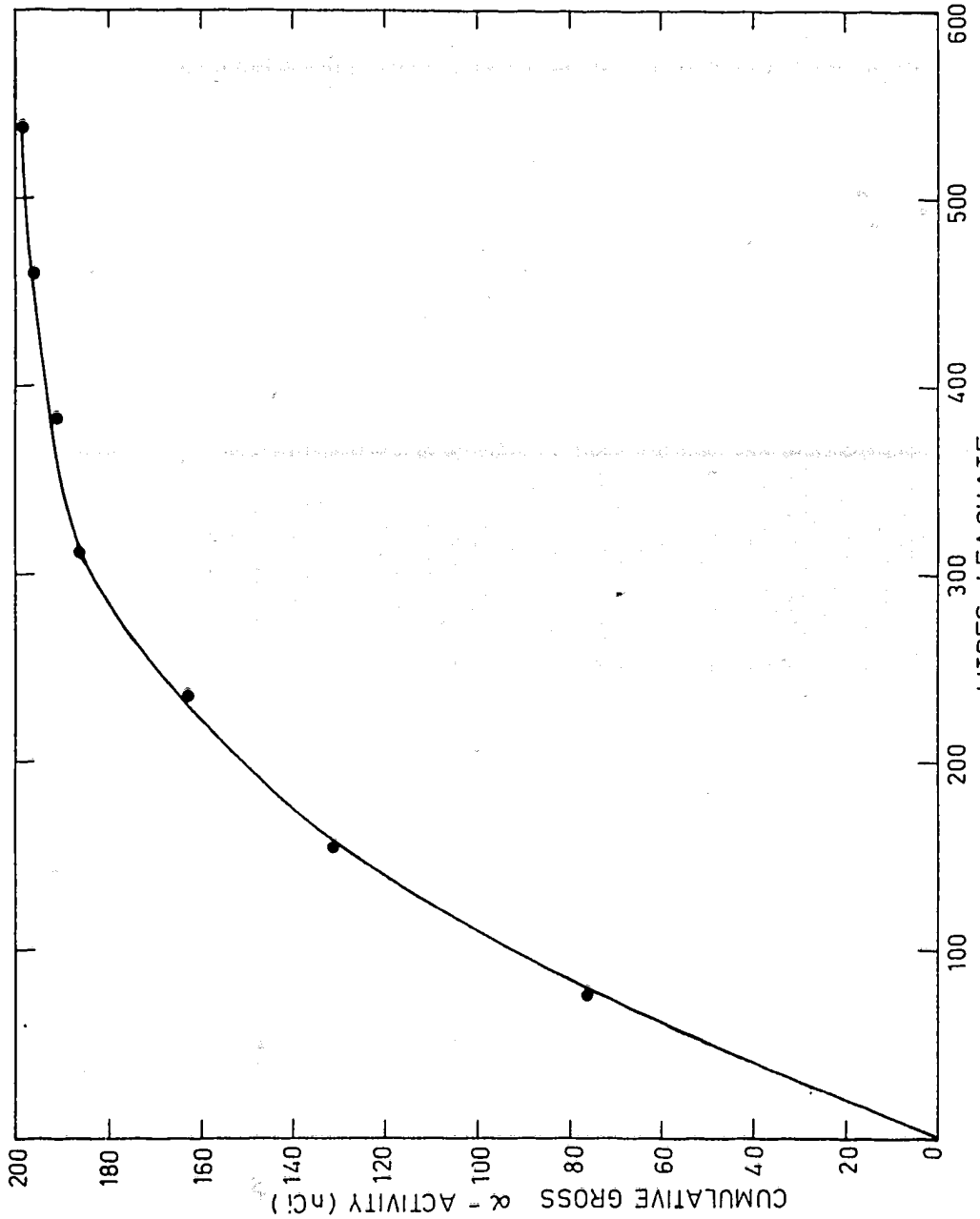

FIGURE 2. LEACHING OF α-ACTIVITY FROM 160 kg SLUDGE

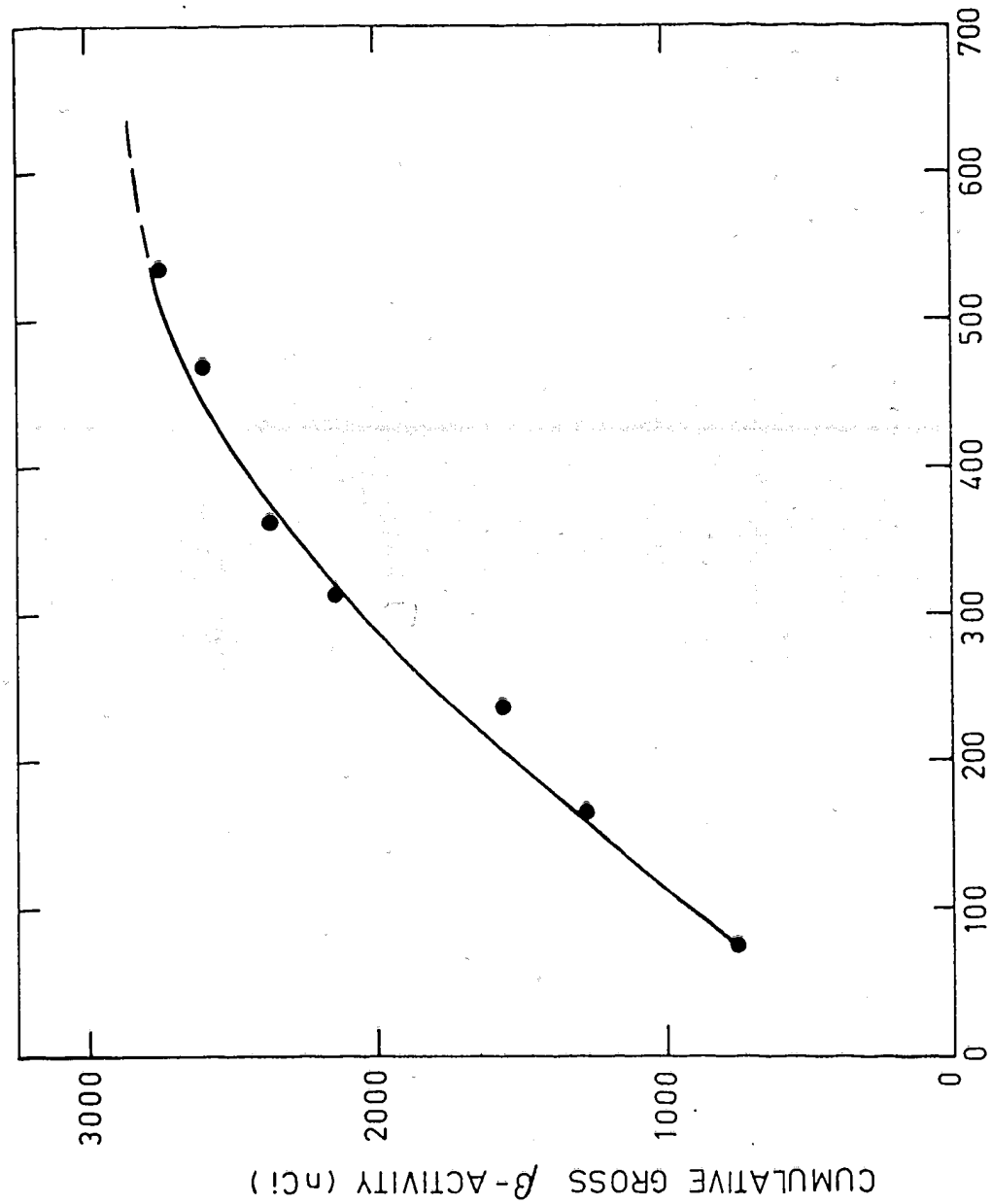

FIGURE 3. LEACHING OF β-ACTIVITY FROM 160 kg SLUDGE

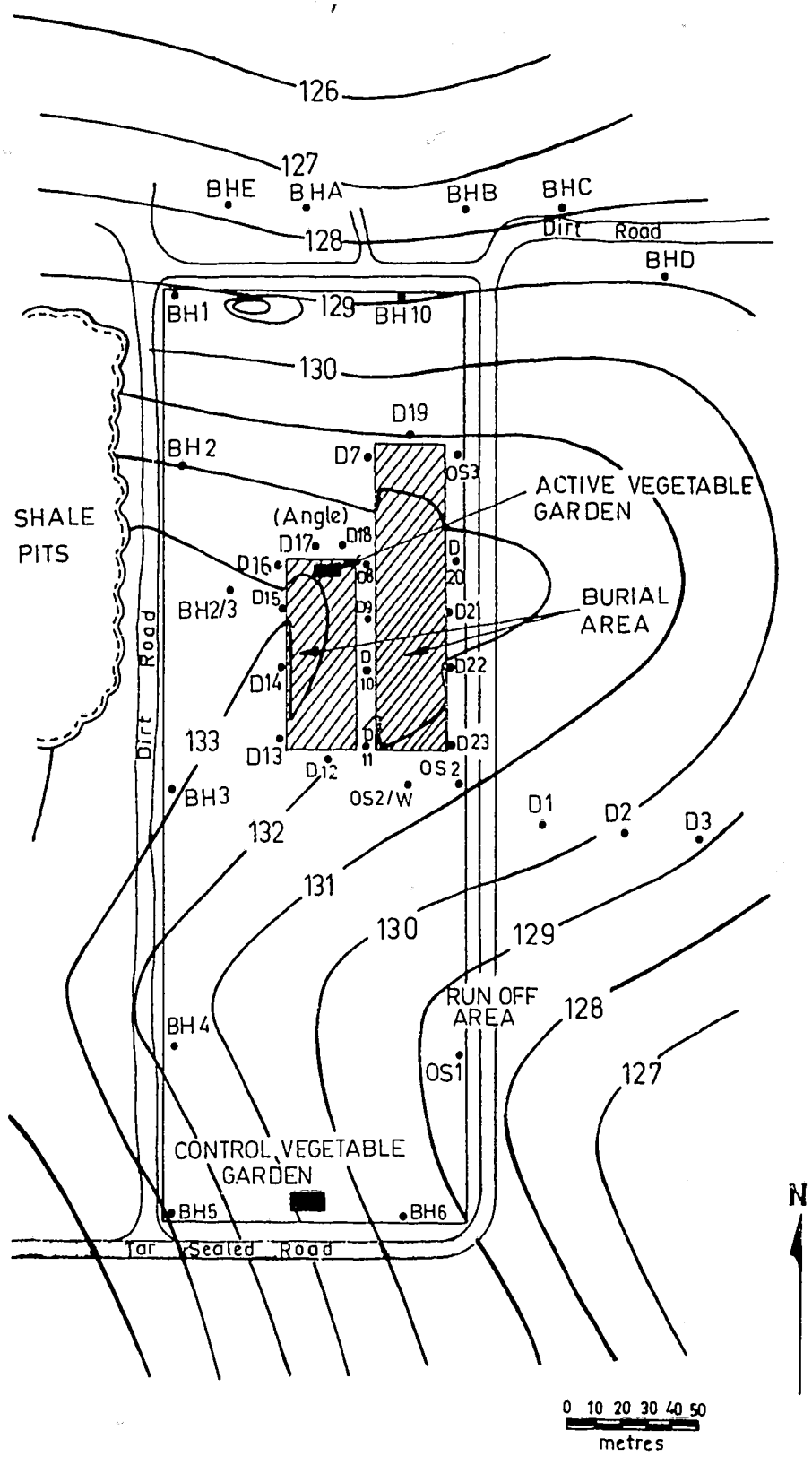

FIGURE 4. BURIAL GROUND SHOWING BURIAL AREA, LOCATION OF BOREHOLES AND SURFACE CONTOURS (IN METRES)

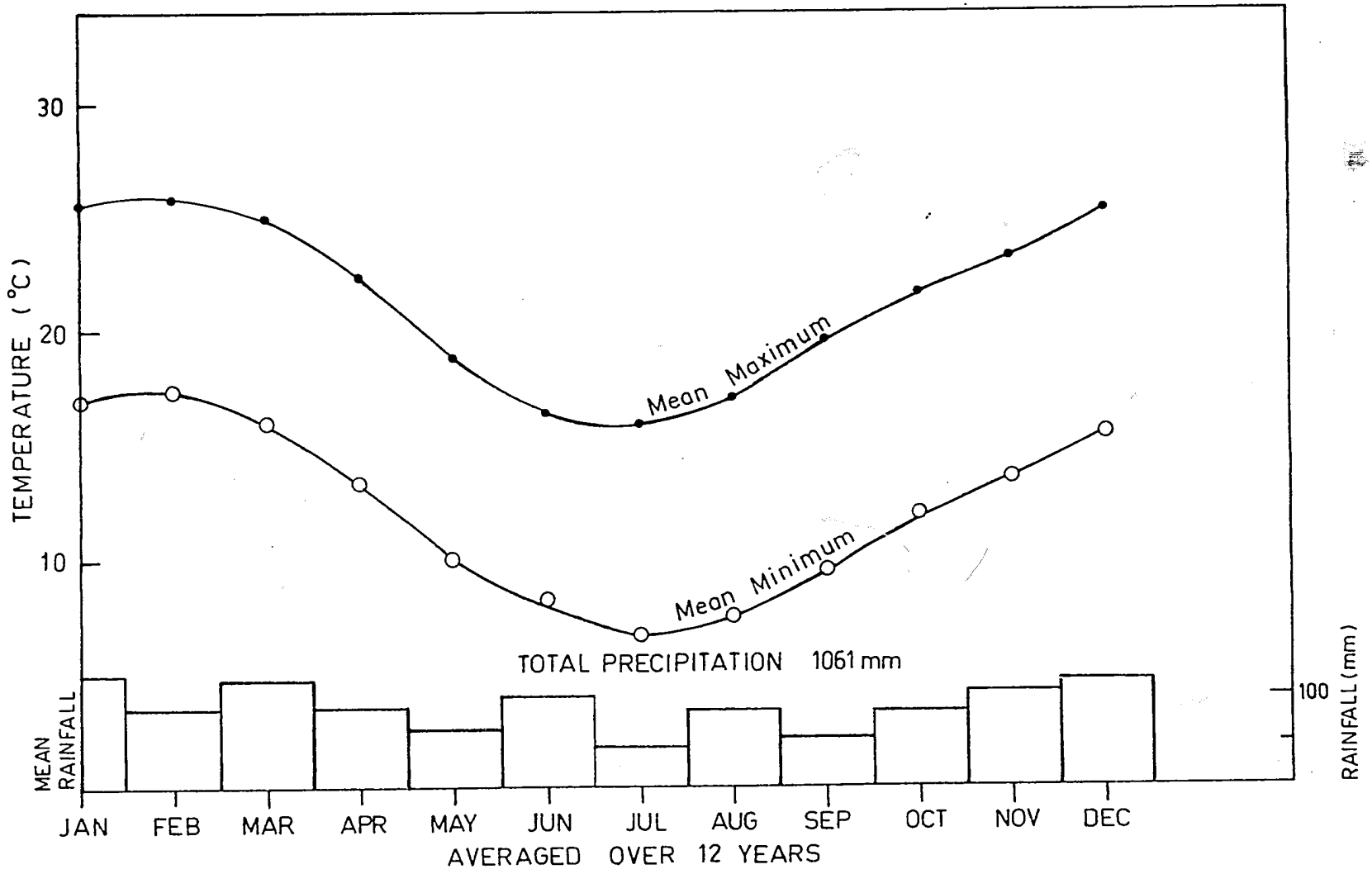

FIGURE 5. CLIMATIC CHARACTERISTICS OF REGION

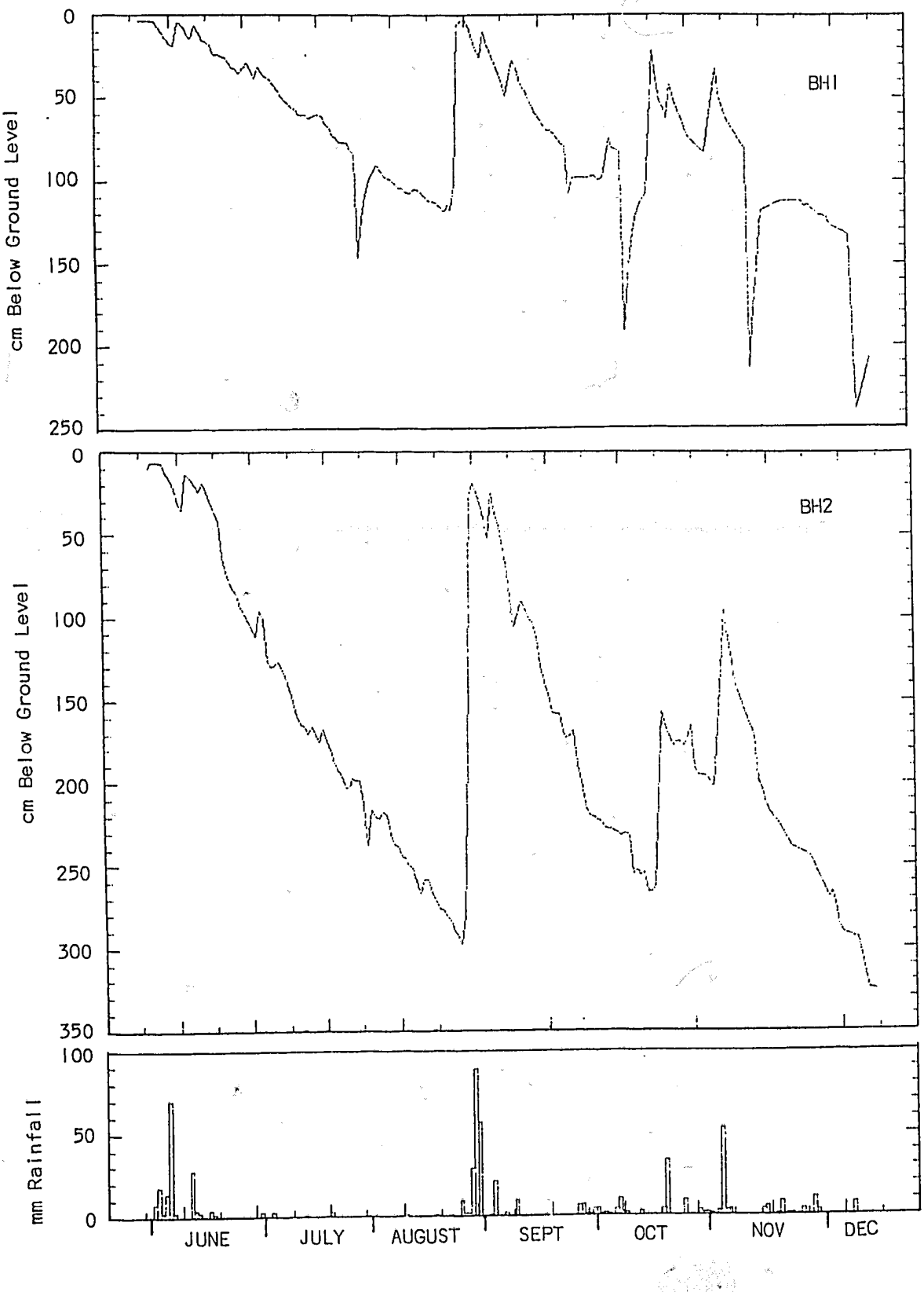

FIGURE 6. HYDROGRAPHS AND RAINFALL DATA (BH1 AND BH2)

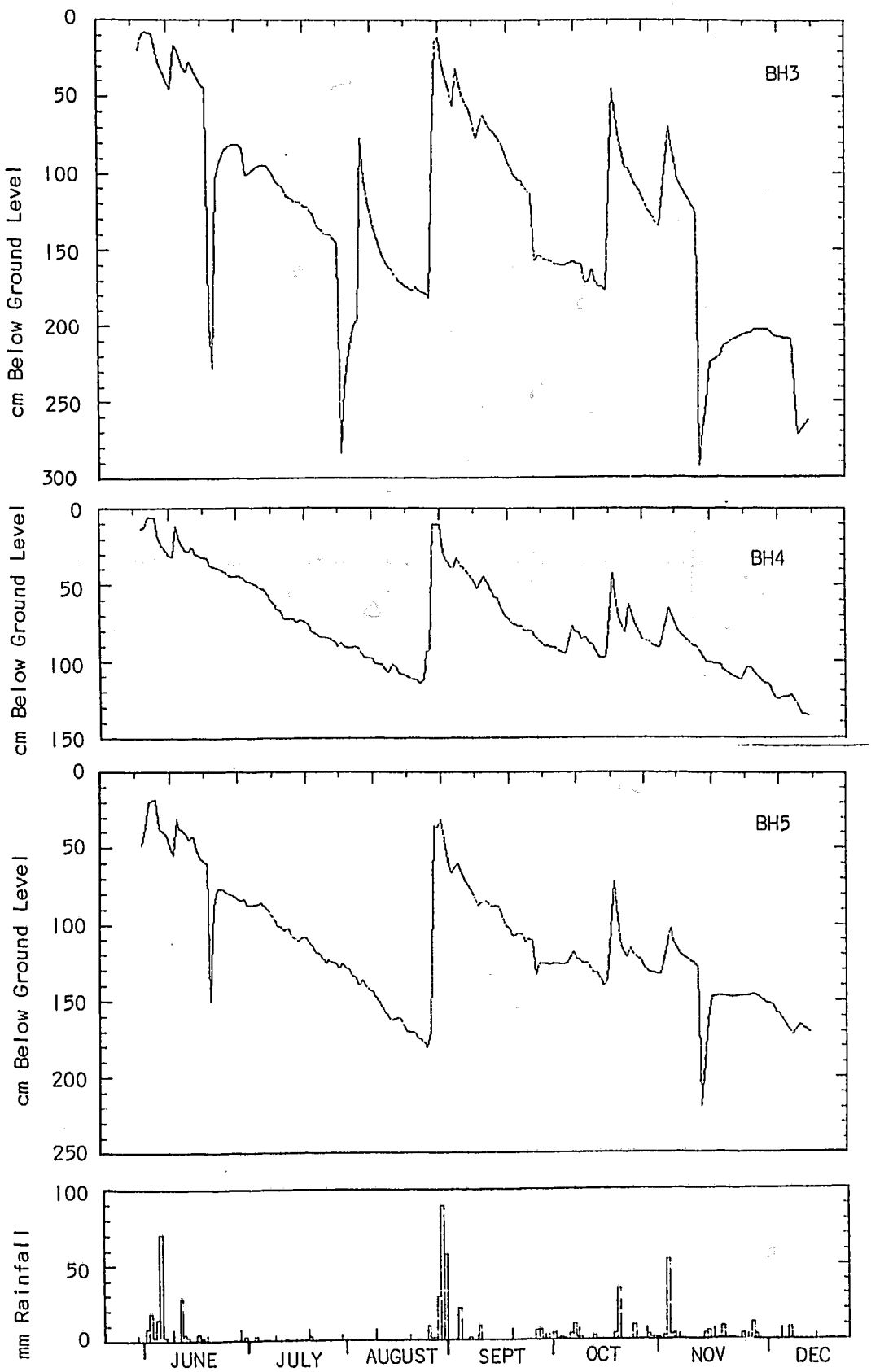

FIGURE 7. HYDROGRAPHS AND RAINFALL DATA (BH3, BH4 AND BH5)

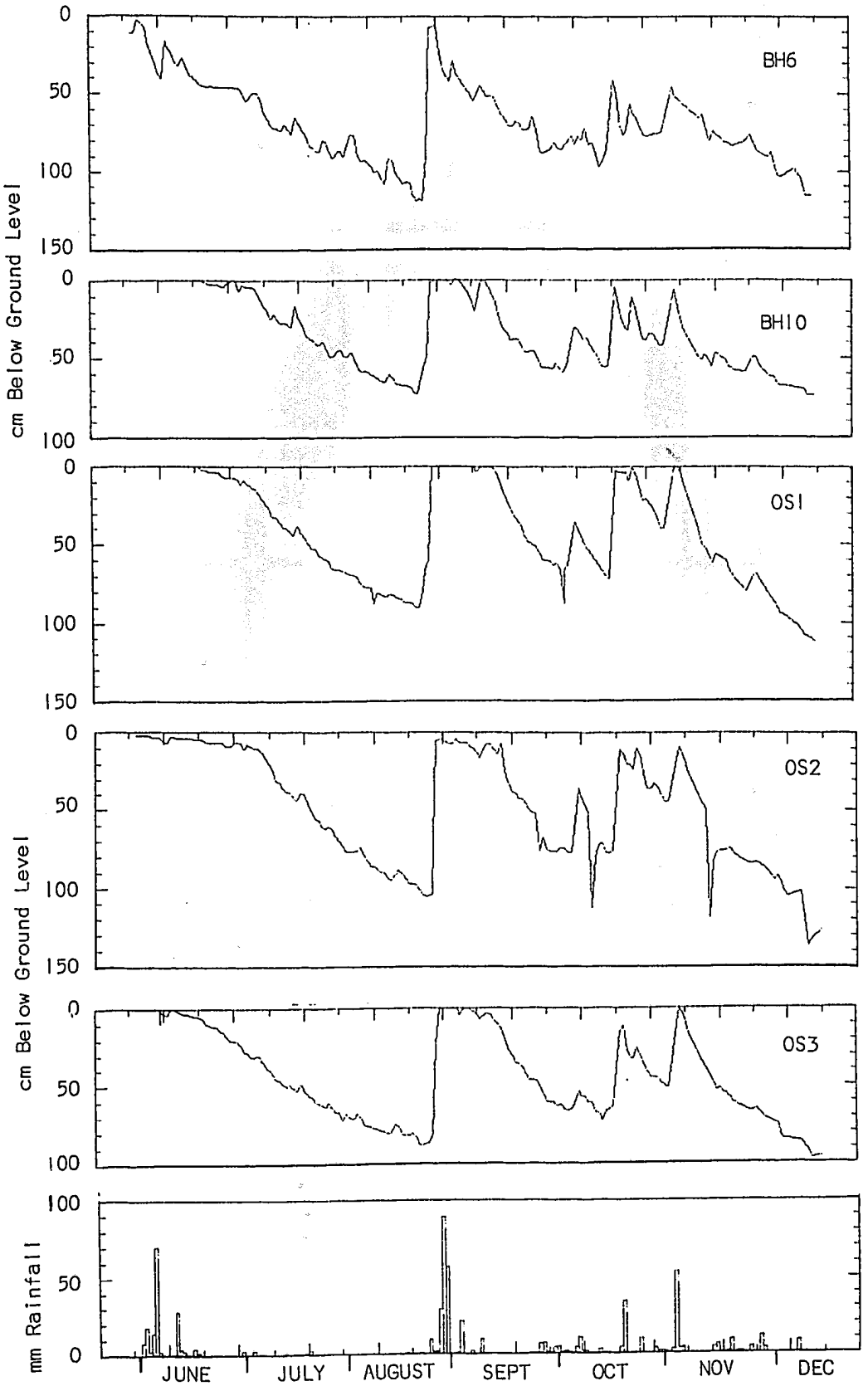

FIGURE 8. HYDROGRAPHS AND RAINFALL DATA (BH6, BH10, OS1, OS2, AND OS3)

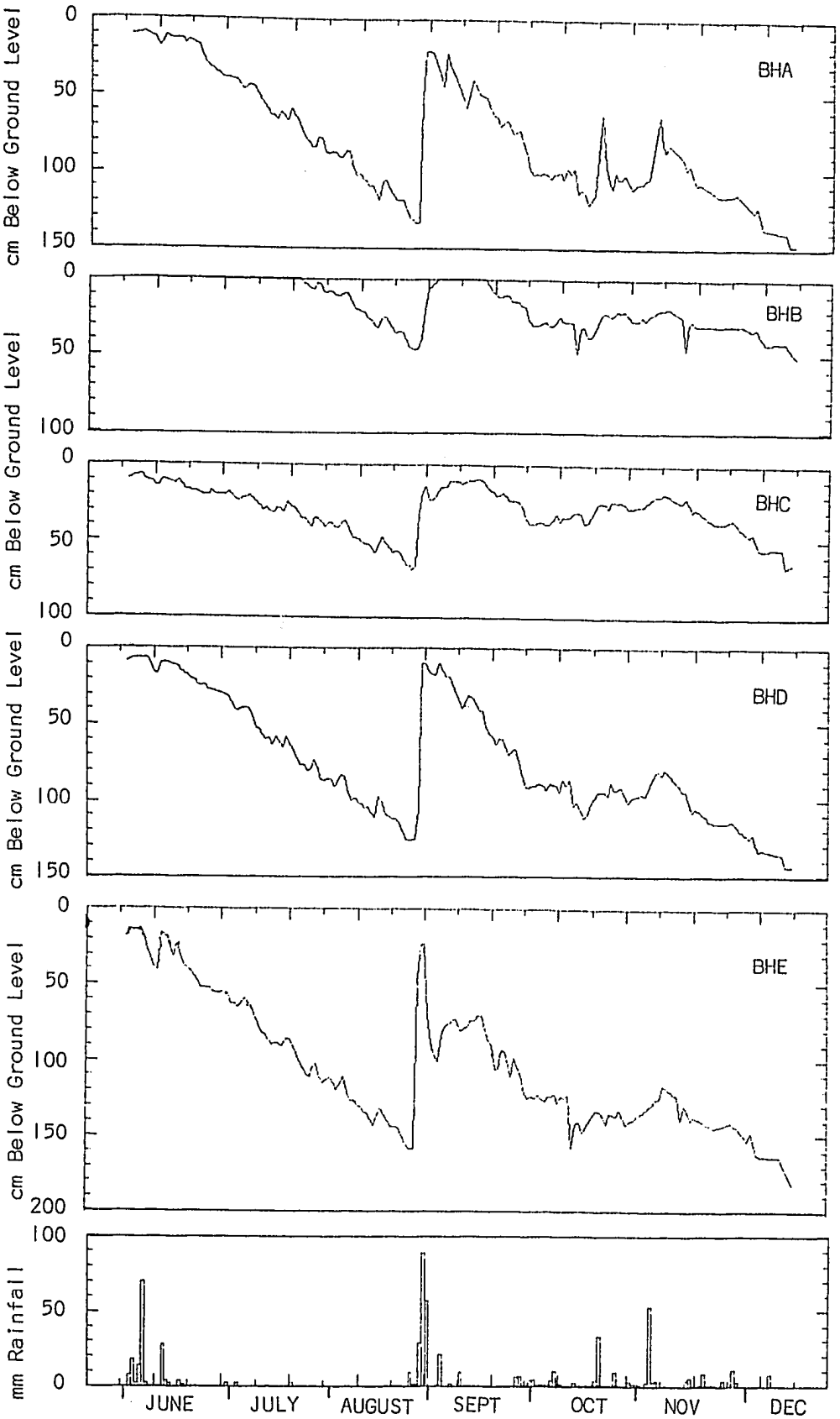

FIGURE 9. HYDROGRAPHS AND RAINFALL DATA (BHA, BHB, BHC, BHD AND BHE)

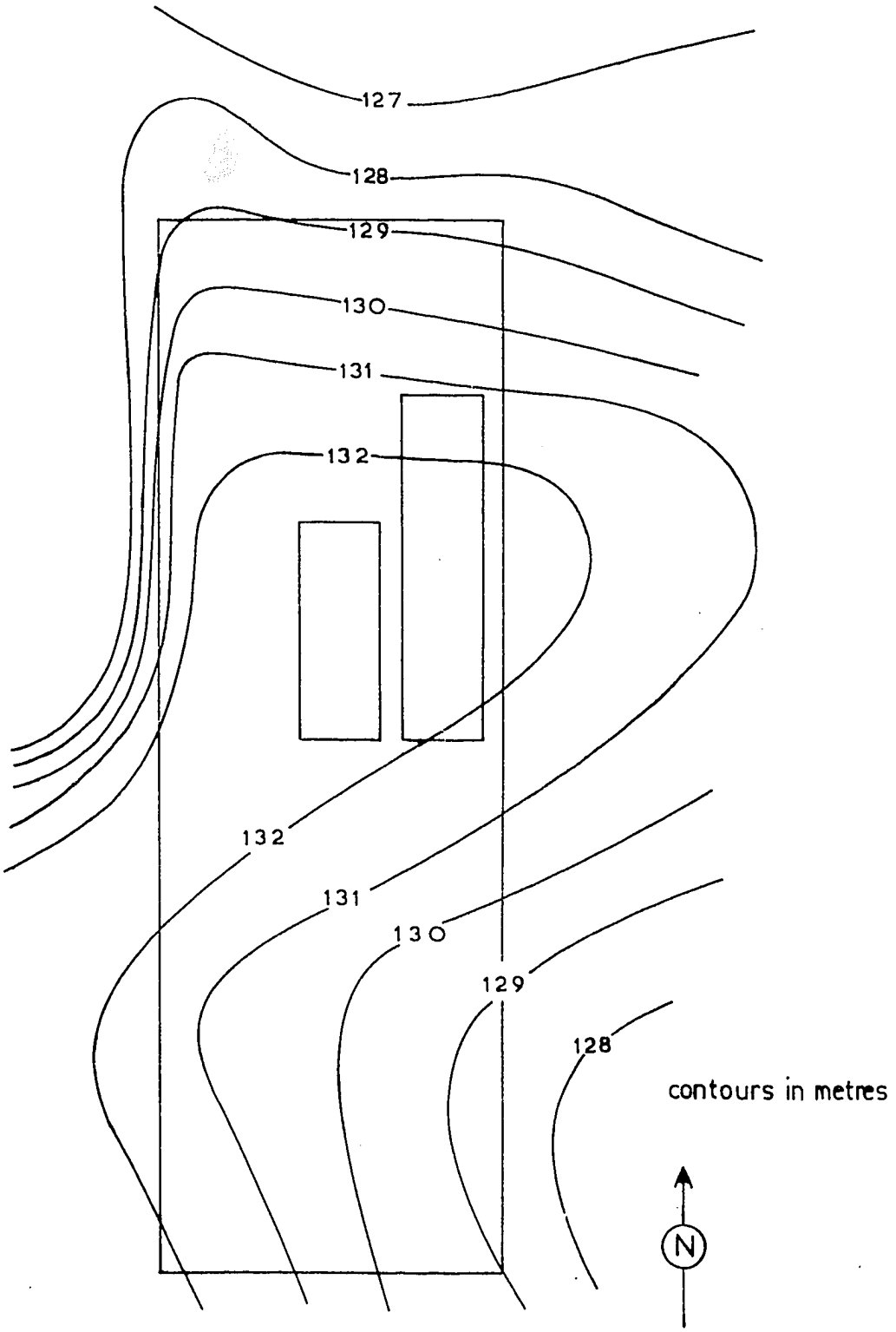

FIGURE 10. GROUNDWATER CONTOURS OF BURIAL GROUND (10.9.74)

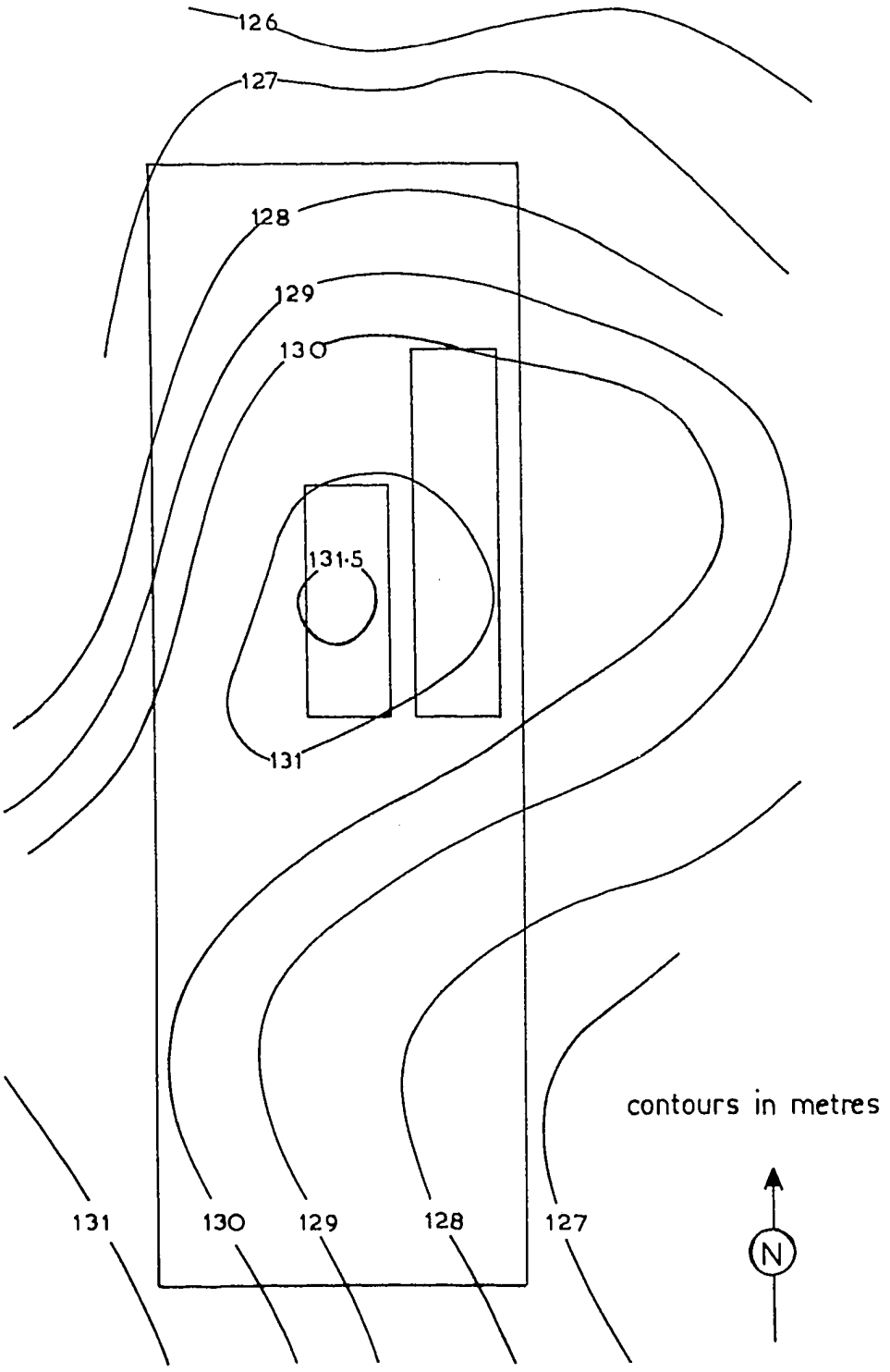

FIGURE 11. GROUNDWATER CONTOURS OF BURIAL GROUND (17.12.75)

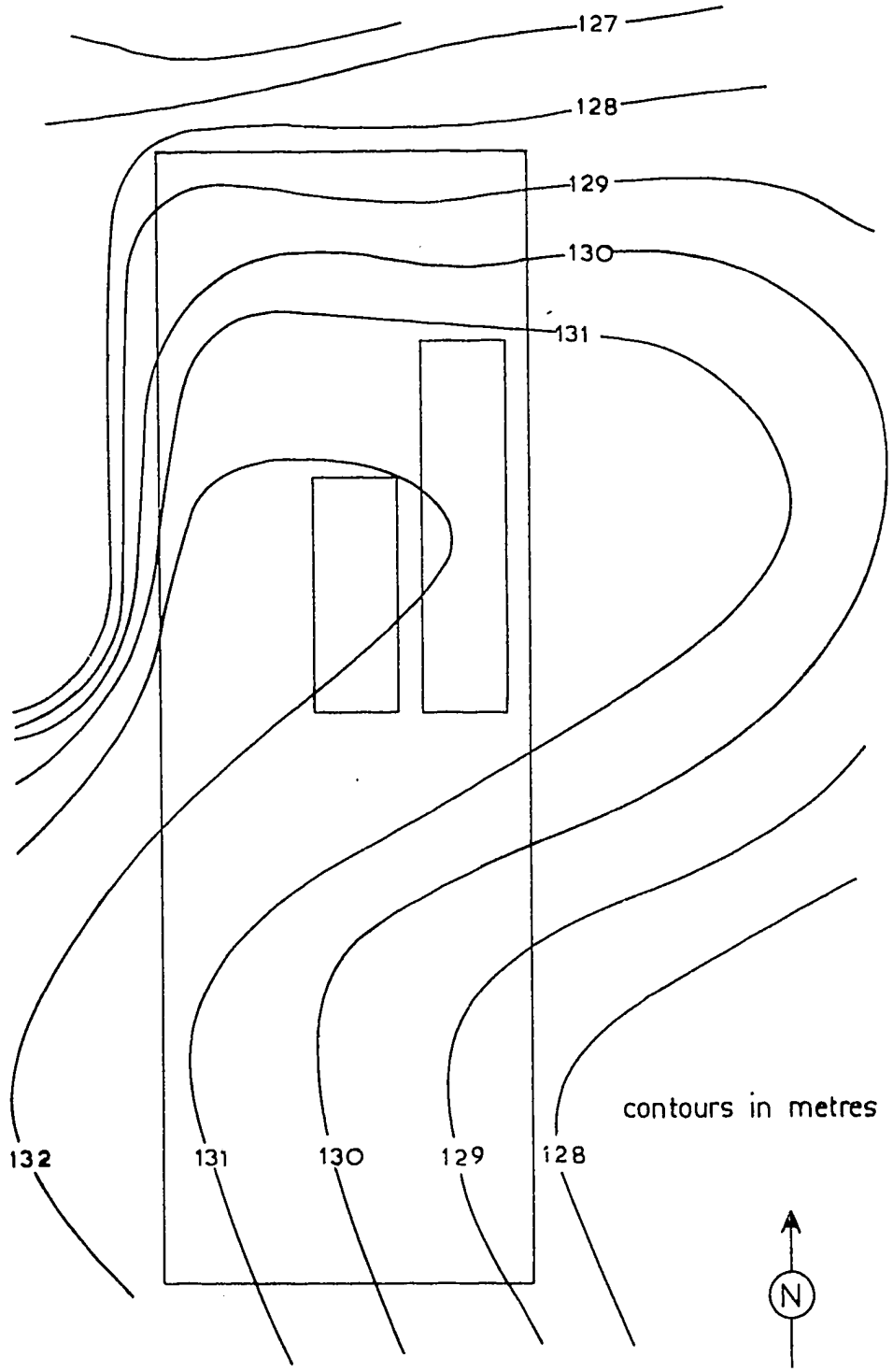

FIGURE 12. GROUNDWATER CONTOURS OF BURIAL GROUND (28.1.76)

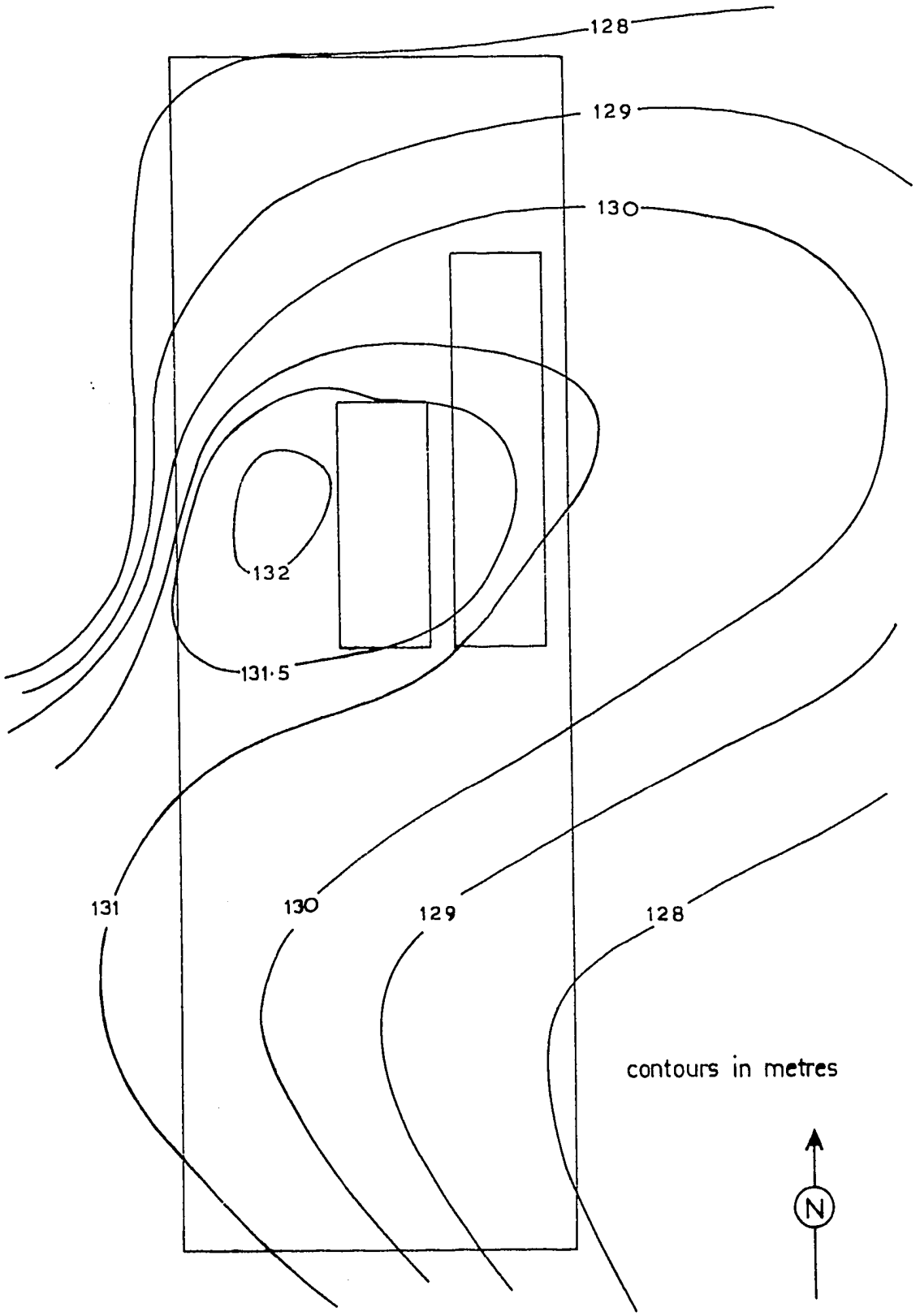

FIGURE 13. GROUNDWATER CONTOURS OF BURIAL GROUND (6.5.76)

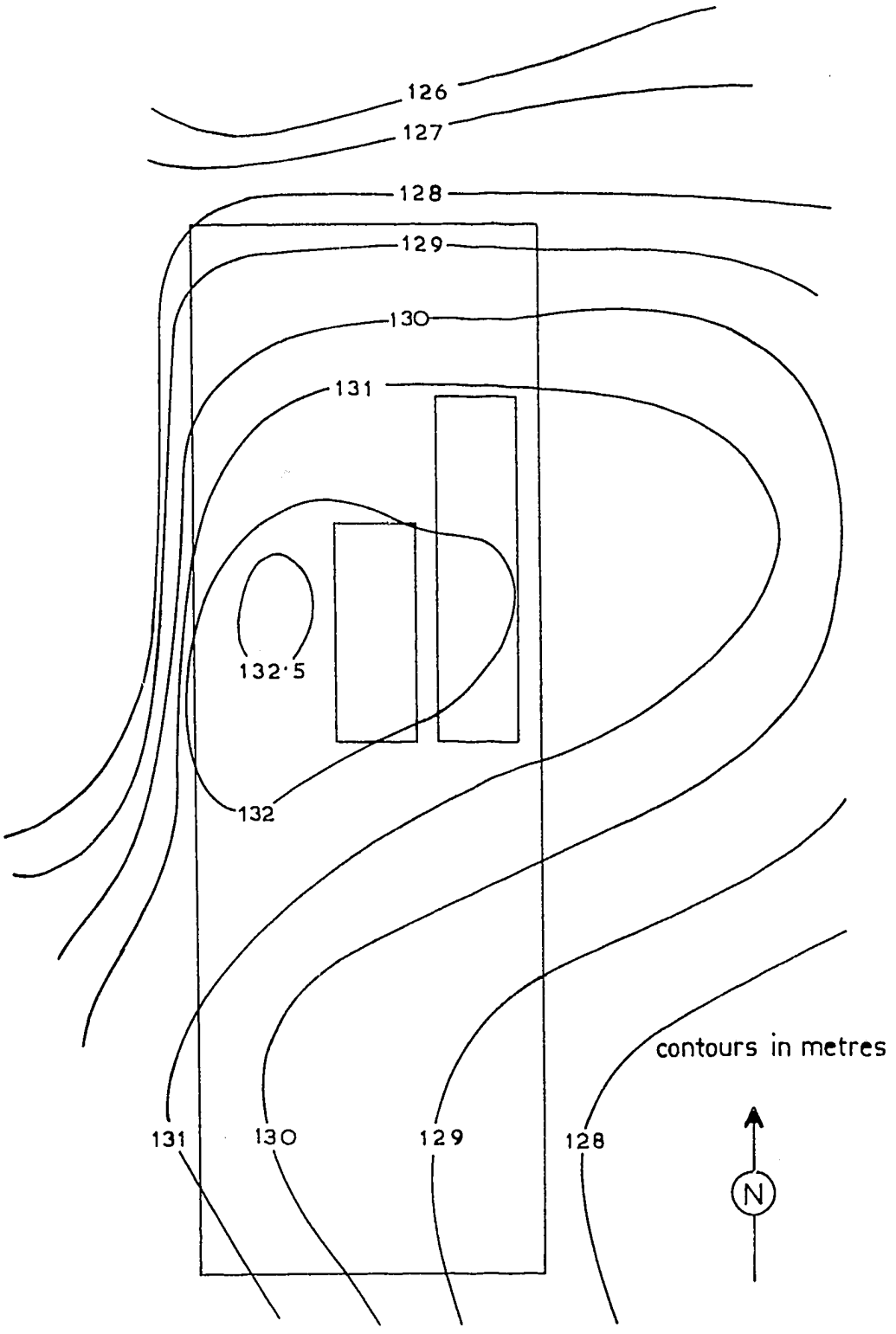

FIGURE 14. GROUNDWATER CONTOURS OF BURIAL GROUND (29.6.76)

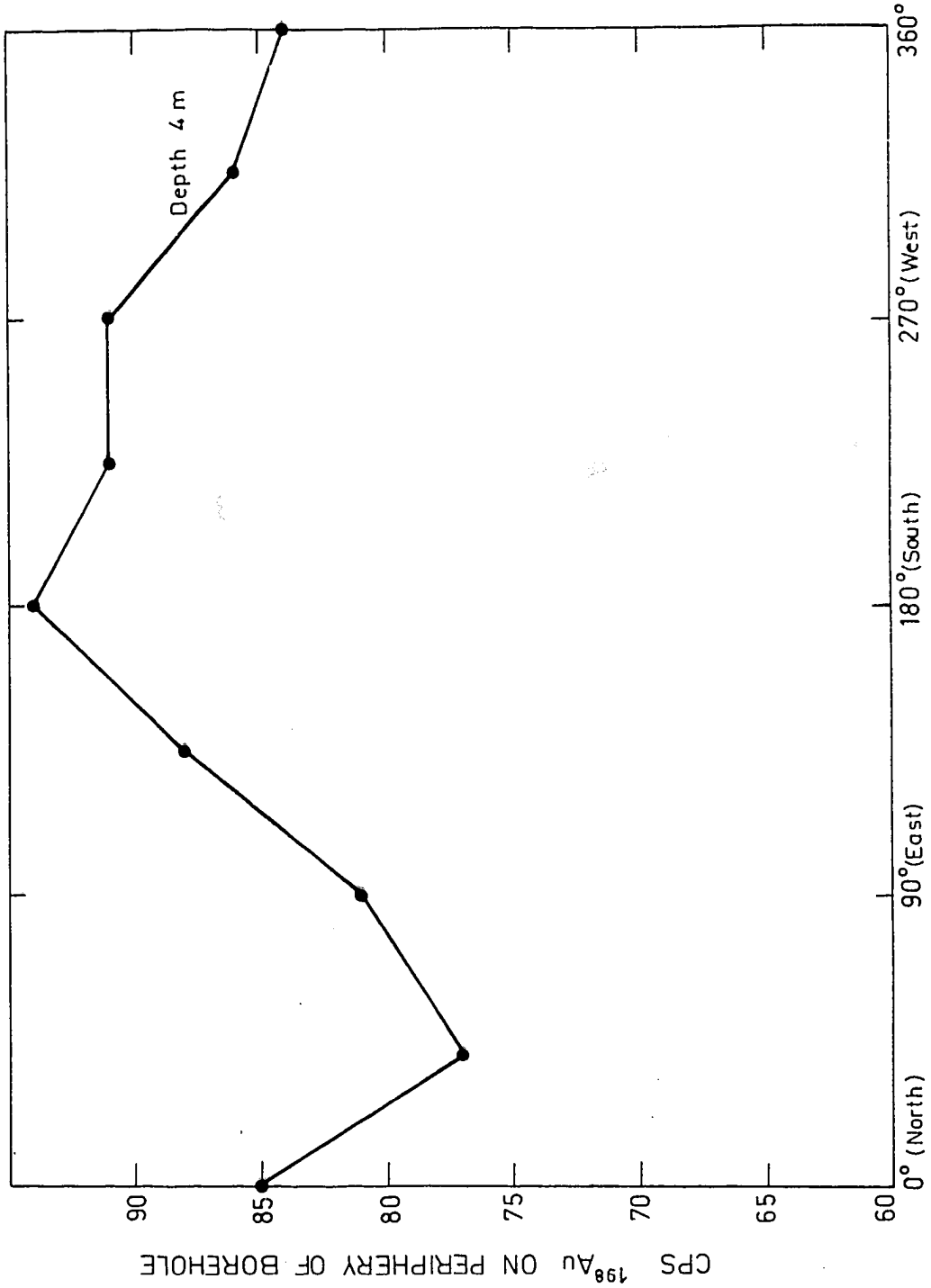

FIGURE 15. DIRECTION OF GROUNDWATER FLOW OBTAINED FROM A COLLIMATED PROBE AT BH2

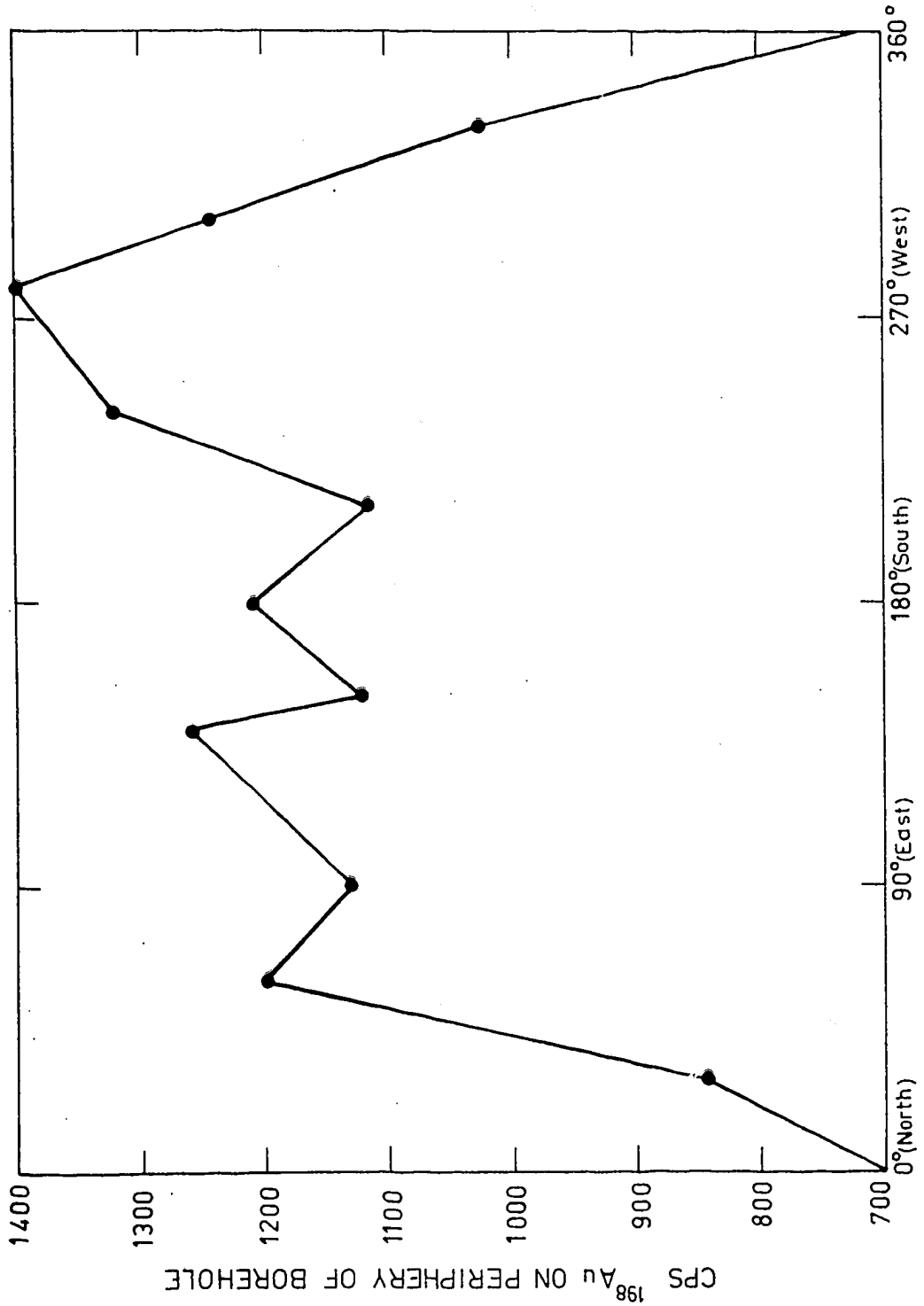

FIGURE 16. DIRECTION OF GROUNDWATER FLOW OBTAINED FROM A COLLIMATED PROBE AT BH10

APPENDIX A

WASTE BURIED IN LITTLE FOREST BURIAL GROUND (1960-1968 INCLUSIVE)

From records of Site Operations Section, AAEC Research Establishment

Activity (mCi) Groups			Fissile Content (g)			Fertile Content (kg)		Be Content (kg)	Volume (m^3)
I	II	III	Pu	U^3	U^5	U	Th		
19.3	1050	3017	6.88	5.21	91.96	59.27	50.65	1730	1675

APPENDIX B

SELECTION OF RADIOACTIVE NUCLIDES [IAEA 1967]

Group I

^{227}Ac, ^{241}Am, ^{237}Np, ^{230}Pa, ^{231}Pa, ^{210}Po, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{226}Ra, ^{228}Ra, ^{228}Th, ^{230}Th, ^{232}U.

Group II

^{41}A, ^{210}Bi (RaE), ^{154}Eu, Mixed Fission Products, ^{233}Pa, ^{210}Pb, ^{223}Ra, ^{224}Ra, ^{222}Rn, ^{90}Sr, ^{233}U, ^{135}Xe.

Group III

^{140}Ba, ^{144}Ce, ^{36}Cl, ^{60}Co, ^{131}I, ^{133}I, ^{114m}In, ^{192}Ir, ^{85}Kr, ^{106}Ru, ^{124}Sb, ^{125}Sb, ^{46}Sc, ^{89}Sr, Th_{nat}, ^{204}Tl, ^{235}U, ^{238}U, U_{nat}, ^{133}Xe, ^{91}Y, ^{95}Zr.

Group IV

^{198}Au, ^{7}Be, ^{82}Br, ^{14}C, ^{45}Ca, ^{38}Cl, ^{58}Co, ^{51}Cr, ^{135}Cs, ^{137}Cs, ^{64}Cu, ^{18}F, ^{55}Fe, ^{59}Fe, ^{42}K, ^{140}La, ^{99}Mo, ^{24}Na, ^{95}Nb, ^{63}Ni, ^{32}P, ^{103}Ru, ^{35}S, T-(in any form other than Group VII), ^{99}Tc, ^{132}Te, ^{65}Zn.

Group V

^{41}A (uncompressed), ^{135}Xe (uncompressed).

Group VI

^{85}Kr (uncompressed), ^{133}Xe (uncompressed).

Group VII

T (as T_2 or HT, or tritium activated luminous paint or tritium gas adsorbed on a solid carrier).

APPENDIX C

AREAS IN WHICH INFORMATION IS NEEDED TO DETERMINE SITE SUITABILITY

A 1974 USGS report on 'Storage of Low-level Radioactive Wastes in the Ground: Hydrogeologic and Hydrochemical Factors', lists 17 areas on which data are needed for evaluating whether proposed or existing sites are suitable for preventing the operation of mechanisms for releasing radioactivity to the environment. These areas are quoted below in approximate order of increasing difficulty and/or cost to obtain:

"(1) Depth to water table, including perched water tables, if present.

(2) Distance to nearest points of ground water, spring water, or surface water usage (Includes well and spring inventory).

(3) Ratio of pan evaporation to precipitation minus runoff (by month for period of at least 2 years).

(4) Water table contour map.

(5) Magnitude of annual water table fluctuation.

(6) Stratigraphy and structure to base of shallowest confined aquifer.

(7) Baseflow data on perennial streams traversing or adjacent to storage site.

(8) Chemistry of water in aquifers and confining beds and of leachate from the waste trenches.

(9) Laboratory measurements of hydraulic conductivity, effective porosity, and mineralogy of core and grab samples (from trenches) of each lithology in unsaturated and saturated (to base of shallowest confined aquifer) zone. Hydraulic conductivity should be measured at different water contents and suctions.

(10) Neutron moisture meter measurements of moisture content of unsaturated zone. Measurements to be made in especially-constructed holes; at least 2 years' record needed.

(11) *In situ* measurements of soil moisture tension in upper 5-10 metres of unsaturated zone; at least 2 years' record needed.

(12) Three-dimensional distribution of head in all hydro-stratigraphic units to base of shallowest confined aquifer.

(13) Pumping, bailing, or slug tests to determine transmissivity and storage coefficients.

(14) Definition of recharge and discharge areas for unconfined and shallowest confined aquifers.

(15) Field measurements of dispersivity coefficients.

(16) Laboratory and field determination of the movement of critical nuclides through all hydrostratigraphic units.

(17) Rates of denudation and (or) slope retreat.".

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