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Indo-British Betwa Groundwater Project

PHASE II OF THE SOIL MOISTURE STUDIES IN THE BETWA CATCHMENT:

A study of soil physical factors controlling recharge

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INDO-BRITISH BETWA GROUNDWATER PROJECT

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CONTENTS

OBJECTIVES

RESULTS

FIGURES

INTRODUCTION

1.1 BACKGROUND

The soil moisture study in the Betwa catchment was carried out between August 1977 and February 1980 in two separate but related phases.

Phase I consisted of an areally extensive study of the variability of soil moisture storage in the 'black cotton soil' areas of the catchment, conducted between August 1977 and September 1978. Phase II was an intensive study of the soil physical processes controlling recharge and water movement in the black cotton soils, carried out at three 'representative' sites during the 1978 and 1979 monsoons and subsequent dry seasons.

The soil moisture study was concentrated on the black cotton soils, since these are the major agricultural soils of the Betwa catchment and also of extensive areas of Central and Western India. They are dark coloured, swelling silty clays derived from the weathering of the Deccan Trap basalts, and are classified as vertisols. A more detailed description of the soils may be found in the Phase I report.

Phase I is covered by two separate but linked reports, 'Phase I of the soil moisture studies in the Betwa catchment: a special report on the Nion and Keothan subcatchments' and the report on the whole of the Phase I study, 'Phase I of the soil moisture studies in the Betwa catchment'. A brief summary of Phase I is included here.

1.2 A SUMMARY OF PHASE I

Phase I was an essential precursor of Phase II: one of the major aims of Phase I was to monitor the behaviour of the soil moisture reservoir throughout an entire year and to investigate the variability of soil moisture in the catchment; this provided information on the areal variability of the soil and a basic understanding of the processes occurring within it, allowing the selection of representative sites for Phase II. The catchment was divided, on the basis of topography and soil depth, into soil areas which were considered to be hydrologically different. An extensive network of 26 access tubes was installed, covering three of the four Areas initially defined: one area of shallow soils (Area I, depths up to 2m) and two areas of deep soils (Areas II and III, depths between 2 and 12 m) (Fig. 1). Observations of soil moisture were made at approximately weekly intervals using an Institute of Hydrology neutron probe. The fourth soil area (Area IV) was not studied since the crops had been sown before installation work could begin and this would have damaged the crops and rendered the sites unrepresentative. Soil depths in Area IV were intermediate between Area I and Areas II/III.

No significant distinction could be found between the deep soil areas, where the moisture contents when wet were found to be exceptionally uniform with both depth and area. The two deep soil areas were subsequently treated as one. Drainage losses were found to be small and since the soil conditions are so uniform the behaviour of the soil moisture reservoir is controlled principally by the rainfall and the abstraction characteristics of the vegetation.

In contrast, the moisture storage and drainage characteristics of the shallow soils were found to be very variable and differed markedly from those of the deep soils. Drainage losses were considerably greater than in the deep soils.

Three sites were subsequently selected for Phase II, one representing the deep soils and two representing the shallow soils. Their locations are shown in Fig. 1. The deep soil site was at Dhaturi, in Area III near to access tubes III$_1$ and III$_2$. The two shallow soil sites were at Nabibag, where the soil depth to weathered basalt was about 2.0 m, and at Nipanian, where the soil depth was 1.3 m. Two sites were selected in the shallow soil area to take account of the greater variability of soil depths. All of the Phase II sites were cultivated.

2. OBJECTIVES

The main objectives of Phase II of the study were to investigate the processes of soil moisture and groundwater recharge and to draw semi quantitative conclusions concerning recharge. The experiments were designed to determine in situ the unsaturated hydraulic conductivity characteristics of the soil at the three sites, so that recharge fluxes could be estimated in the wet season using Darcy's law. In the post monsoon period, deep drainage from the profile (recharge) was estimated using the zero flux plane method.

3. METHOD

3.1 BASIC PRINCIPLES

Water in the soil moves in response to water pressure gradients, expressed in terms of total hydraulic potential Ψ, representing the potential energy of the water within the soil. The two principal components of total potential are the gravity potential ψ_g and the matric potential ψ_m. The gravity potential is the potential of the water arising from its position within the earth's gravity field. The ground surface is normally taken as the datum (zero gravity potential) so that the gravity potential below the soil surface is always negative. The matric potential is due mainly to the surface tension acting on the air-water interfaces in the soil pores and is always negative in unsaturated soil, although it becomes positive in saturated soil, when it is equivalent to the positive pressure head.

The two components are therefore both negative in unsaturated soils and are additive,

$$\Psi = \psi_m + \psi_g$$

so that total potential is always negative in unsaturated soil.

Potential is commonly expressed in terms of centimetres of water head (cm H_2O). Total potentials between 0 and -800 cm H_2O are generally measured using tensiometers and lower potentials (higher tensions) can be measured using gypsum resistance blocks.

Total potential data are presented as 'potential profiles', the total potentials measured within a soil profile being plotted against depth. eg. Fig. 20. In these Figures gravity potential, ψ_g, is represented by the dashed line; when expressed in units of cm H_2O, ψ_g at any point in the soil is equivalent to the depth below ground level in centimetres. The area to the right of the dashed line represents the unsaturated phase and the area to the left, the saturated phase. The water table corresponds to the depth at which the potential profile crosses the gravity potential line (ie where $\psi_m = 0$).

The direction of the potential gradient indicates the direction of the moisture flux. The zero flux plane (ZFP) is a point in the potential profile at which the gradient is zero, indicating no flux, about which flux either diverges or converges. In the dry season, a divergent ZFP forms and separates an upper zone of upward flux (supplying evaporation) from a lower zone in which the flux is downward (drainage), eg Fig. 20, profile 5.11.79, 1.2 m depth. A convergent ZFP occurs during the early stages of the rewetting of the profile, when the upper zone is starting to drain while upward flux is still occurring in a zone beneath, eg. Fig. 16 profile 2.12.78, 0.8 m depth.

When an identifiable divergent ZFP is present within a profile the depletion of moisture storage may be partitioned into upward and downward fluxes attributable to evaporation and drainage. This forms the basis of the 'zero flux plane method' for determining evaporation and drainage. (Bell 1976).

Water movement in both saturated and unsaturated soil is described by Darcy's Law:

$$v = -K \frac{d\Psi}{dz}$$

where v is the flux

K is the hydraulic conductivity of the soil

$\frac{d\Psi}{dz}$ is the potential gradient

The hydraulic conductivity (K) is a sensitive function of both the volumetric moisture content (θ) and the matric potential of the soil (ψ_m). The relationship between θ and ψ_m is unique for a particular soil (or even soil horizon) and is known as the moisture release characteristic.

3.2 THEORY OF THE METHOD

The experiments were designed to determine the hydraulic conductivity characteristics of the soil in situ, so that recharge during the monsoon could be estimated from Darcy's law using the in situ derived conductivity, together with the potential gradients measured under the natural soil moisture regime.

The method used for obtaining the unsaturated hydraulic conductivity was the so called 'instantaneous profile' technique (Watson 1966).

A site is selected and neutron probe access tubes and mercury manometer tensiometers are installed. Tensiometers are placed at regular depth intervals to the base of the zone in which the conductivity is to be measured. After the soil profile has been virtually saturated, the surface of the soil in the experimental plot is covered to prevent further gains or losses of water at the soil surface. Since evaporation from the plot is prevented, all losses from the plot occur as drainage and unsaturated water movement under the instrumented centre of the plot can be assumed to be vertically downwards. Moisture contents and total potentials are measured at regular intervals as the profile drains.

Under these conditions the total moisture storage change above any given depth in the profile represents the drainage flux of water (v) through that depth during the relevant period of time. The potential gradient ($d\Psi/dz$) at the same depth can be derived from the tensiometer data so that the conductivity can be calculated from Darcy's Law,

$$= - K_{(\psi_m,\theta)} \frac{d\Psi}{dz}$$

As the profile drains, the fluxes, conductivities, moisture contents and matric potentials decrease and the conductivity at different depths in the profile can therefore be derived for a range of values of moisture content and matric potential.

3.3 EXPERIMENTAL SITES

At each of the three Phase II sites, two replicate sets of instruments were installed on adjacent plots about 6m apart. One set of instruments was used for measuring the hydraulic conductivity (the 'covered' plot) and the other was used to monitor the natural, undisturbed soil moisture regime (the 'open' plot). Each instrument set consisted of two neutron probe access tubes and one set of mercury manometer tensiometers. The tensiometers were installed at 0.2 m depth intervals to a depth of 2.4 m at Nabibag and Dhaturi and at 0.15 m intervals to 1.35 m at Nipanian (reaching hard weathered basalt). At the Nabibag and Nipanian sites, gypsum resistance blocks were also installed on the natural regime (or 'open') plots to measure soil matric potential when the measuring range of the tensiometers was exceeded. (The gypsum block data were not in fact used in the interpretation because the potentials near the zero flux plane remained within the measuring range of the tensiometers throughout the year). The soil around each instrument set was protected from disturbance by an open galvanised iron pipework frame about 1.5 m square and 0.5 m high. All observations and maintenance work were carried out from a ladder placed across the frame to prevent damage to the ground surface and crop. The Nabibag and Dhaturi sites were equipped both with storage raingauges (generally read daily) and tipping bucket gauges with solid state loggers. The Nipanian site was equipped with a manual gauge which was read daily. Fig. 2 shows a typical site layout and other site details are given in Table 1.

3.4 EXPERIMENTAL PROCEDURE

3.4.1 Covered plots

Once the soil has been wetted to near saturation during the monsoon the ground surface on one plot at each of the sites was covered with a 5 x 5 m black plastic sheet through which the tensiometers and access tubes protruded. Any holes in the sheet around the instruments were sealed with PVC tape. A large tent was erected over the plot to prevent rainwater collecting on the plastic sheet and to reduce thermal effects on the tensiometers. The area around the edges of the plastic sheet was kept free of weeds since their moisture abstraction could have created significant lateral potential gradients under the covered plot. Observations of soil moisture were made at approximately two-day intervals initially but as the drainage rate became very slow, the interval between observations was increased. At Nabibag the tensiometers were read at the same time as the soil moisture observations were made, but at the other two sites, which had resident observers, the tensiometers were read twice daily, at 06.00 hrs and 18.00 hrs.

At the Nabibag and Nipanian covered plots, observations were started on 25 July and 8 September 1978 respectively, and continued until 12 March 1979 when the instruments were removed. Observations at Dhaturi were started on 30 June 1979 with both plots 'open'. Plot 2 was subsequently irrigated on 31 August to restore the profile to saturation since the monsoon had withdrawn early and the profile had dried out considerably. This plot was then covered and operated until March 1980.

The behaviour of the tensiometers at 2.2 and 2.4 m at the Nabibag and Dhaturi sites was sometimes difficult to explain. Anomalies could have arisen due to swelling pressures or due to the low conductivity, causing slow response to potential changes. This might have been exacerbated by smearing of the clay around the porous cup during installation.

3.4.2 Open plots

The natural regime plots were cultivated and weeded at the same time as these operations were carried out in the surrounding cultivated areas. Wheat was sown on all of the open plots and at sites where the sowing was carried out late, a supplementary irrigation of about 10 mm was applied immediately prior to sowing. Observations were made at the same time intervals as at the hydraulic conductivity plots but were continued after observations at the covered plots were discontinued. Observations were continued at Nabibag and Nipanian until the end of the 1979 monsoon.

Table 1 Phase II site details

	Nabibag	Nipanian	Dhaturi
Access tubes			
Reading depth interval (m)	0.20	0.15	0.20
Maximum depths (m)	2.60	1.20 - 1.50	2.80 - 3.00
Tensiometers			
Depth interval (m)	0.20	0.15	0.20
Maximum depth (m)	2.40	1.35	2.40
Gypsum blocks			
Depth interval (m)	0.20	0.30	
Maximum depth (m)	1.40	1.50	
Raingauges			
Manual	✓		✓
Recording	✓	-	✓
Start of observations	17.7.78	8.9.78	30.6.79
Conductivity plot covered	25.7.78	12.9.78	31.8.79
Site closed	23.9.79	23.9.79	25.10.80

3.5 AREAL REPRESENTIVITY OF THE EXPERIMENTAL SITES

The Dhaturi site is considered to represent well the behaviour of the cultivated soils in Areas II and III (the deep soils) because of the remarkable uniformity of soil water conditions in those Areas, as demonstrated by the Phase I programme.

However, the validity of the extrapolation of the results obtained at Nabibag to Area I (shallow soils) as a whole is less certain because of the much greater variability of soil water conditions and because this site was on the boundary between Areas I and II/III. No useful evidence was obtained for the Nipanian site for reasons discussed later.

4. RESULTS

The main findings are summarised as headings to the sections which follow. The material relevant to each is presented and discussed under the appropriate heading.

4.1 The hydraulic conductivity of the soil decreases progressively with depth, reaching very low values below the structured upper 1.5 m of the profile.

The conductivity characteristics derived for the Nabibag and Dhaturi* sites are given in Figures 3 to 6. The first two diagrams show the conductivity at the two sites as a function of matric potential and the latter two show the conductivity as a function of moisture content.

The main features of the conductivity characteristics derived for the Nabibag and Dhaturi sites are:

1. At both sites there is a rapid decrease of conductivity with depth for any given value of matric potential between 0 and - 80 cm H_2O.

2. At the Nabibag site there is the suggestion that this trend of conductivity decreasing with depth is mainly in the upper 1.5 m; below 1.5 m the conductivity seems to be relatively uniform with depth and very low.

3. At both sites conductivity decreases very quickly with falling matric potential (increasing tension). For example, at Nabibag the saturated conductivity at 0.9 m is 26 mm/day, drops to 1.0 mm/day at a matric potential of - 70 cm H_2O and 0.1 mm/day at a matric potential of - 100 cm H_2O.

4. The Dhaturi curves (Fig. 3) show a sharp change of gradient below a conductivity of about 1.0 mm/day. This could represent the transition between macrostructure conductivity and matrix conductivity ie. the conductivity of the fissure system remaining after the cracks have closed, and the conductivity of the clay matrix itself.

5. The plots of conductivity against water content (Figs. 5 & 6) show that very small changes in water content accompany very large changes in

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* It was not possible to derive the conductivity characteristic for the Nipanian site as an upward potential gradient persisted in the upper 0.6 m of the profile at the covered plot. This was attributed to the abstraction of moisture from beneath the covered plot by the laterally extending roots of shrubs and small trees along the field boundary beside this site.

conductivity. At both sites a reduction of volumetric moisture content of 0.02 reduces the conductivity by two orders of magnitude or more.

The general form of the curves is remarkably interconsistent and ordered although there is some uncertainty as to the saturated values, as at the initial stage of drainage, moisture changes in the upper part of the profile tended to be too rapid to use this technique. However, the modest extrapolation shown in the diagrams gives saturated values which are reasonable but probably err on the low side. The lower conductivities were difficult to determine in these clay soils: as the conductivity decreased, the drainage rate became so low that the moisture content changes in the profile were too small to be measured accurately, even over intervals of several weeks. At Nabibag the moisture storage change in the entire covered profile between 12 December 1978 and 5 March 1979 (76 days) was only 7.0 mm, equivalent to a drainage rate of only 0.09 mm/day. Changes within individual layers of the profile were therefore extremely small.

The potential gradients within the profiles also became very small, often less than 0.05 cm H_2O/cm depth, making them difficult to determine accurately.

This is illustrated by the series of potential profiles from the Dhaturi covered plot shown in Fig. 7.

4.2 Residual structure remaining after the soil profile has rewetted during the monsoon provides relatively high conductivities in the upper structured soil layer when it is saturated or close to saturation.

In the Phase I report, the hydrological importance of soil cracking and its influence on soil structure and hydraulic conductivity was discussed and the distribution of cracking in the soil profile was inferred from the patterns of soil moisture depletion. In the deep soil areas the depletion patterns indicated that the degree of cracking declined with depth, becoming negligible below a depth of about 2.0 m at cultivated sites and about 4.0 m at uncultivated grass and scrub sites. The cracking is largely responsible for creating soil structure, which enhances the hydraulic conductivity of the saturated and nearly saturated soil. Both structure and conductivity therefore decline correspondingly with depth implying that the clay/silt below the zone of seasonal moisture change is unstructured and therefore only poorly conductive.

The inference from Phase I that conductivity decreases with depth is confirmed by the conductivity data from both sites, although the Nabibag data suggests that the conductivity is low and relatively uniform below 1.5 m. At the Dhaturi site the conductivity characteristics for depths below 1.3 m could not be derived because of the rise in the water table after unseasonal rainfall in November.

The rapid decrease in conductivity in the range of matric potential between 0 and - 100 cm H_2O is evidence that the principal conductive pathways for water movement in the soil are large pores which are full of water only at low tensions. The rapid decrease of conductivity in this range of matric potential is associated with a moisture content reduction of about 0.02 and this indicates that these large pores occupy only about 2% of the volume of the soil.

Thus the higher conductivities (in excess of about 1 mm/day) are attributable to the large pores or 'macrostructures' the most probable form of which are planar cracks and fissures remaining between the soil peds after the shrinkage cracks have closed after rewetting. Once the macrostructures have emptied, ie at matric potentials below about - 100 cm H_2O, the conductivity is generally between 0.1 and 1.0 mm/day and falls steadily with decreasing matric potential. In these circumstances appreciable water fluxes could only occur where potential gradients are very steep, a situation which never occurred within the draining profile.

The decrease in the size of the structures with depth is illustrated by the decreasing air entry values shown by the water release characteristic curves of both sites.

Matric potentials were plotted against volumetric moisture content during the drying cycle to derive the curves which are shown in Figs 8 & 9. The curve for each depth was derived from a large number of points which, for the purposes of clarity, are not shown. The moisture characteristics of soils are largely controlled by their texture, but soil structure is also important, particularly at high matric potentials (low tensions).

The saturated moisture content at 0.2 m at both sites is considerably higher than at the other depths where the saturated moisture contents are all similar. This, and the steepness of the curve from saturation, indicates that the soil structure at 0.2 m is very open and easily drained: a reduction of matric potential to - 10 cm H_2O is accompanied by a moisture decrease of almost 0.04 at Dhaturi and more than 0.02 at Nabibag.

The curves for depths below 0.2 m all exhibit a marked plateau which indicates that when the matric potential decreases from saturation, the moisture content remains virtually unchanged until a critical value of matric potential in reached. This critical value is known as the 'air entry value' and corresponds to the matric potential at which the largest pores in the soil begin to empty of water. As the matric potential decreases further, progressively smaller pores are emptied and the moisture content decreases. The decrease of air entry values with depth shown in Fig. 8 illustrates the decrease in the size of the largest pores down the profile.

The saturated moisture contents at Dhaturi are about 0.02 VMC lower than at Nabibag. The more confused sequence of moisture characteristics at Nabibag may reflect a change of soil texture with depth as the black cotton soil begins to merge into weathered basalt at a depth of about 2.0 m.

4.3 During the early stages of the monsoon the rewetting of the soil is very heterogeneous but as the monsoon progresses a perched water table (saturated zone) forms in the soil profile at a depth of about 1.5 m and saturation thereafter advances from this depth both upwards and downwards.

Sequences of potential profiles illustrating the wetting process at Dhaturi plots 1 and 2 during the 1979 monsoon and at Nabibag during the 1978 monsoon are shown in Figs 10, 11 and 13 respectively. (Both the Dhaturi plots were 'open' until the end of August).

The principal points of interest in the Dhaturi figures are as follows:

1. Initial wetting is very sporadic and the early potential profiles (not shown) are very confused, due to irregular wetting down fissures and lateral absorption. Only when potentials have risen to about - 500 cm H_2O does a clear picture start to emerge. (Figs 10 and 11).

2. As the wetting of the profile proceeds during the monsoon, a zone of saturation (a perched water table) appears, not at the soil surface, or at the base of the profile, but in the middle of the profile at about 1.5 m, with unsaturated conditions remaining above and below. This is shown by the profiles of 29.7.79 in Figs 10 and 11. The saturated zone then gradually expands upwards and downwards to saturate the complete profile. This is also illustrated in Fig. 12 which shows the behaviour of the saturated zone, interpreted from the Dhaturi plot 1 tensiometer data.

In 1979 (Fig. 13) the wetting process at the Nabibag site proceeded in exactly the same way as at Dhaturi, with a saturated zone forming in the middle of the profile, between 1.0 and 1.6 m (profile 6.8.79) and expanding both upwards and downwards (profile 10.8.79). See also Fig. 14. However, the monsoon ceased after about 10 August and this profile shows the greatest extent of the saturated zone in 1979. The initial wetting process at Nabibag was not observed in 1978, as the tensiometers had not been commissioned at the start of the monsoon.

The initial appearance of saturated conditions in the profile above about 1.5 m indicates that the conductivity at this depth is too low to allow drainage at a rate comparable to the rate of input from above so that the water 'ponds up' above this layer. Drainage occurs from the base of this temporary perched water table, which also expands slowly and, at Dhaturi, merges with the water table rising from below (supplied by the unsaturated drainage from the perched water table above). At Nabibag the latter stage of the process did not occur in 1979 and saturated continuity with the underlying water table in the weathered basalt was not achieved.

4.4 Once the entire soil profile is saturated and in saturated continuity with the underlying water table, the potential gradients in the soil profile tend to zero, implying little further drainage.

This is illustrated by the sequences of potential profiles from the Dhaturi sites shown in Figs 10 and 11. The potential gradient within the saturated zone which initially forms in the profile is downward, indicating continuing drainage, but as the zone expands, the gradient decreases, becoming close to zero when the whole profile is saturated. The decreasing gradient can be seen in Fig. 10 but is particularly clearly shown in Fig. 11 by the sequence of potential profiles for the period 29.7.79 to 10.8.79 between the 0.8 and 1.4 m depths. The very small potential gradients in the upper 1.6 m of the fully saturated profiles can be seen in both Figures.

Although the initial wetting up process at Nabibag was not observed in 1978, the tensiometers were installed later in that monsoon and the potential profiles from this site (Fig. 15) also show that when the entire profile is saturated, potential gradients in the upper profile are very small, as at Dhaturi. Later in the 1978 monsoon slight upward potential gradients appear at Nabibag (Fig. 16) profiles 22.8. and 12.9.78) suggesting that the soil may be acting as a confining layer to the weathered basalt beneath. (Note: this applies only to Nabibag, not Dhaturi).

The very small potential gradients which exist at both sites once the entire profile is saturated indicate that further drainage is virtually negligible in spite of the fact that the conductivity is at a maximum in this state. This suggests that at Dhaturi, the flux is limited by the very low conductivity in the lower profile below the structured zone. The earlier downward flux indicated by the downward potential gradients can be explained as satisfying residual storage in the lower profile.

Fig. 17 shows the downward flux for the 0.9 m depth at Dhaturi for the period between July 1979 and January 1980, the soil moisture deficit (with respect to saturation) in the measured profile below 0.9 m and the daily rainfall. The fluxes were calculated using the Darcy forumla for the 0.9 m depth; this depth was selected because the potential data required for calculating the gradients (the 0.8 and 1.0 m depths) were the most reliable over the periods concerned. A saturated conductivity of 7 mm/day was adopted (See Fig. 5) but the calculated fluxes should be regarded as approximate as the conductivity data have been extrapolated in the matric potential range between 0 and -30 cm water. Once a zero flux plane had formed during the dry periods the drainage through the 2.9 m depth (the base of the measured profile) was calculated using the ZFP method (section 3.1).

Two main drainage events are shown, the first during the 1979 monsoon season and the second at the end of November 1979, following heavy winter rainfall. The latter event was very unusual as the rainfall at Dhaturi between 27 and 29 November was 150 mm, ten times the long term mean rainfall for the month.

Irrespective of the errors involved, the drainage hydrographs for both events show that the drainage flux (at 0.9 m) is high initially but declines to less than 1.0 mm/day when the entire profile is saturated. At the same time the deficit in the lower part of the measured profile decreases to zero and the coincidence of these events seems to indicate that the drainage flux declines because all of the available storage below the 0.9 m depth has been filled. After the entire profile is saturated the drainage flux decreases slowly to about 0.1 mm/day (in response to the reduction of the potential gradient).

The total drainage flux shown for the July/August event (29/7 - 22/8) is 39.5 mm but the flux for the first 3 days of the event (indicated by the dotted lines in (Fig. 17) was calculated for the 0.7 m depth since the data for the 0.9 m depth were not reliable. During these 3 days, 8.0 mm of the calculated flux through the 0.7 m depth went into storage in the layer between 0.7 and 0.9 m so that the total drainage flux through the 0.9 m depth during the whole event was 31.5 mm. Before the event the moisture deficit in the measured profile below 0.9 m was 28 mm so that there is an apparent surplus of flux amounting to about 4 mm. This could have gone towards making up any deficit below the measured profile.

The similarity between the calculated flux and the deficit in the measured profile indicates that 7 mm/day probably represents almost the lowest possible value of conductivity for the 0.9 m depth; if a lower conductivity had been adopted, the calculated flux would not have been large enough to satisfy the measured deficit between 0.9 and 2.9 m. It is difficult to justify a choice of an upper value for the conductivity but it is unlikely that it would exceed 14 mm/day. This value of conductivity would increase the calculated flux to 63 mm, leaving an apparent surplus of 35 mm to restore any deficits below the measured profile. This surplus is very large considering the very low specific yield of the yellow clay.

However, irrespective of the value of the conductivity adopted, the potential gradients show clearly that once the entire profile is saturated, there is no further significant downward flux for the remainder of the monsoon. Further work would be required to refine this conclusion and quantify the flux accurately.

The November event contrasts with the monsoon event in that the antecedent deficit below 0.9 m was 11 mm and the calculated flux into the zone was 24 mm, leaving an apparent surplus of 13 mm. On this occasion, a surplus would not be expected since there is unlikely to have been a deficit below the measured profile, as, before the event, the water table had only fallen to 2.5 m. This apparent surplus could be explained either by lateral losses (unlikely), or by abstraction by the developing root system of the wheat crop from below 1.0 m (also unlikely). Another possible explanation would be that between August and November the conductivity was reduced below the adopted 7.0 mm/day figure (derived for the August period data) by slow, long term swelling of the clay further closing the macrostructures. Adoption of a conductivity of 3 mm/day would reduce the calculated flux for the November event to 10.5 mm and still satisfy the antecedent deficit. Evidence supporting the hypothesis of slow continued swelling is that the saturated profile water content below 0.9 m was 713 mm in July and 720 mm in November, implying that further slow re-wetting of the clay did in fact take place.

4.5 In normal monsoon seasons the soil storage is totally replenished in all soils and the water table rises to the surface. However, in rainfall deficient monsoons, as in 1979, storage in intermediate depth soils (as at Nabibag) is less likely to be entirely replenished than in the very deep soils.

In 1978, the monsoon rainfall in the southern portion of the Betwa catchment was about 10% above average but in 1979 it was very deficient. The 1979 monsoon rainfall totals for Nabibag and Dhaturi were very similar; 496 mm and 523 mm respectively, compared to the long term mean monsoon rainfall totals for Bhopal and Vidisha of 1107 and 1230 mm.

(a) Comparison of soil water replenishment at Nabibag in 1978 and 1979.

The difference in the timing and degree of soil water replenishment following the onset of the monsoons of 1978 and 1979 can be seen by comparison of Figs 14 and 18 which show the behaviour of the saturated zone, interpreted from the tensiometer data. In 1978 the saturated zone was within 0.3 m of the surface for four weeks during August and early September whereas in 1979 it only rose to within 0.3 m of the surface for about a week, and then only intermittently. Of greater significance is the difference in the downward extent of the saturated zone; in 1978 the base of the measured profile (2.4 m) had become saturated by mid July (when observations began) and remained saturated throughout that year. In contrast, in 1979 the wetting front of the saturated zone barely reached down to 2.0 m, and saturated hydraulic continuity with the water table in the underlying weathered basalt aquifer was never achieved. This is confirmed by the water levels in dug wells near to the site; in 1978, water levels reached the surface but in the 1979 monsoon the water levels did not rise above about - 7m. After the monsoon ceased, the saturated zone contracted rapidly due to evaporation and drainage losses and had virtually disappeared within two weeks. (See Fig. 19).

(b) Comparison of soil water replenishment at Nabibag and Dhaturi in 1979.

At Dhaturi the soil moisture and groundwater storage were fully replenished; the saturated zone (indicated by the tensiometers) extended from the base of the measured profile almost to the surface (Fig. 12), although only for a few days, a much shorter period than normal. Water levels in nearby dug wells also rose to the surface indicating that saturated hydraulic continuity with the permanent water table below had been achieved.

In contrast to Dhaturi the soil moisture and groundwater storage at Nabibag was not fully replenished in 1979 and the soil moisture measurements show that the maximum storage in the measured profile was 60 mm less than in 1978.

The difference in the response of the two sites arises largely because there is more available storage capacity to be filled in the soil/groundwater system at Nabibag than at Dhaturi. At Nabibag, weathered basalt, with a specific yield of between 2% and 10%, occurs below 2.4 m, but at Dhaturi, 'yellow clay' extends down to at least 6 m and this has a specific yield of less than 0.5%. Although the water table at both sites falls to about the same level below the surface before the monsoon, it remains within the 'yellow clay' at Dhaturi, so that considerably less water is required to saturate the zone below the measured profile than at Nabibag. At both sites recharge rates are restricted by the very low conductivity of the unstructured clay below about 1.5 m but this is of less importance at Dhaturi since there is much less storage to be filled below the measured profile.

However, in soils which are shallower than at Nabibag (mainly in the West of the catchment) and especially where the depth to weathered basalt is less than about 1.5 m recharge rates will be less restricted because the layer of unstructured clay is absent.

5. CONCLUSIONS

The evidence from the Dhaturi site, representing the deep soils, suggests that in these areas, the structured clay 'black cotton soil' forms an upper aquifer system which is virtually isolated from the more conductive weathered basalt aquifer beneath by the intervening thickness of unstructured and poorly conductive 'yellow clay'. During the monsoon, downward fluxes constituting recharge through the base of the structured soil layer appear to be very small indeed, but are nevertheless sufficient to restore the profile beneath to saturation. The cultivated deep soils can therefore be modelled as a tank, with an almost non leaking base, and a capacity of about 280 mm (varying somewhat with crop). The tank overflows when full to produce surface runoff, which includes a component of interflow through the macrostructures into ephemeral drainage channels. The interflow probably drains only the capacity of the macrostructures (less than 2% *of the upper 1.5 m of the profile) which would yield a post monsoon* baseflow of not more than 30 mm. The predominant mechanism of water loss from the soil'tank' is evaporation.

The situation in the shallow soils is very different. The Nabibag evidence was not entirely conclusive because the profile depth was about 2.2 m, intermediate between the shallow and deep soils (as initially defined). However, the evidence concerning soil structuring and its influence on conductivity indicates that where the soils are shallower, ie.less than 1.5 m in the cultivated areas (deeper beneath grass/scrub) the unstructured and poorly conductive layer is absent so that the structured clay/silt soil and the weathered basalt form a composite aquifer. Recharge fluxes are less restricted because the unstructured layer is absent, but the Nabibag data suggest that downward (recharge) fluxes are small once the water table has risen to the surface. This seems to indicate that there is little continuity between the river system and the weathered basalt at Nabibag. Elsewhere continuity may exist and downward fluxes are likely to continue throughout the monsoon.

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We wish to thank Mr A L Kidwai the Project Leader, and Mr H R Versey, the UK team leader, together with their staff, for their support and assistance during this project. We are also grateful for the advice and interest of Dr J V Sutcliffe, Institute of Hydrology, and Dr R Herbert, Institute of Geological Sciences.

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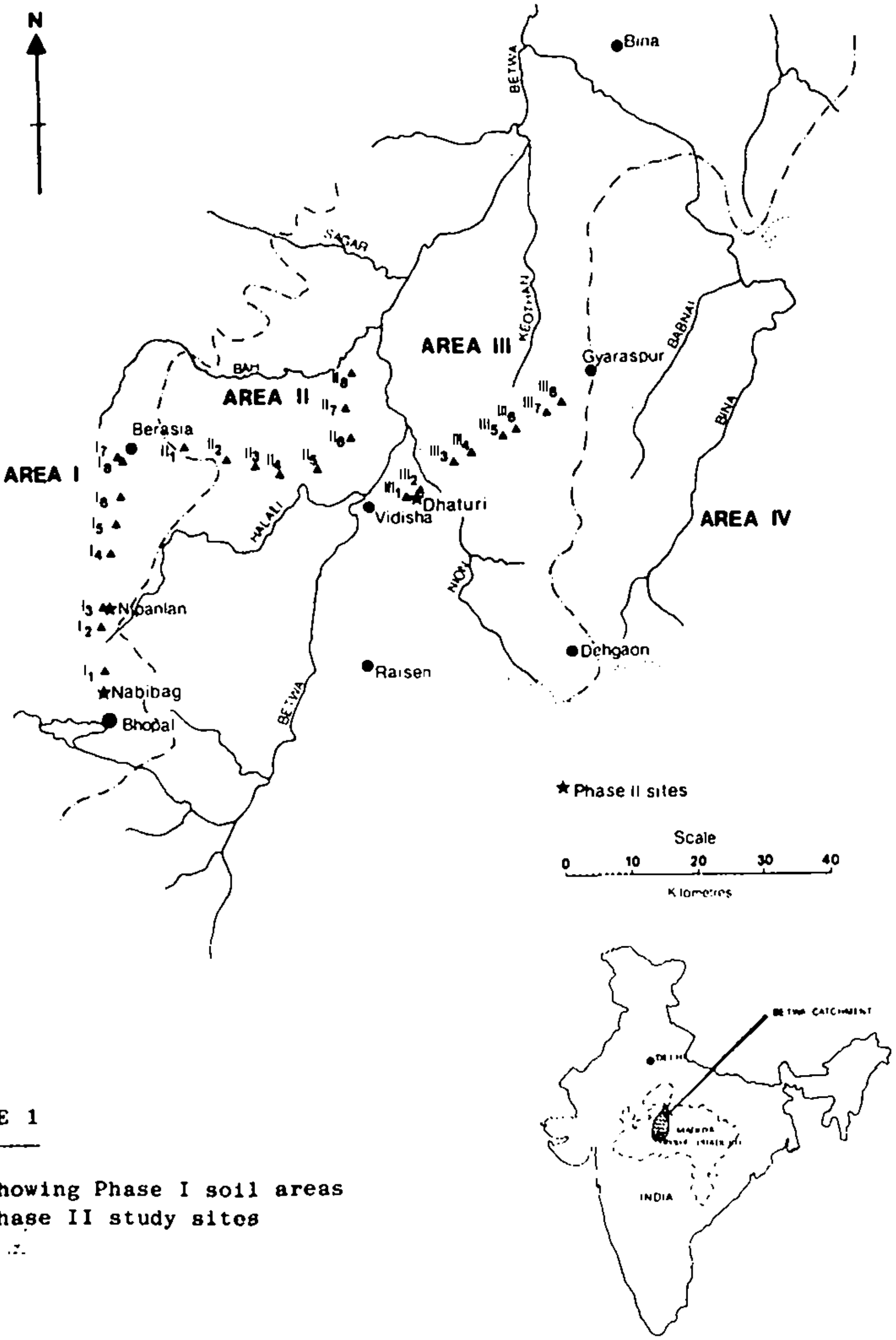

FIGURE 1

Map showing Phase I soil areas and Phase II study sites

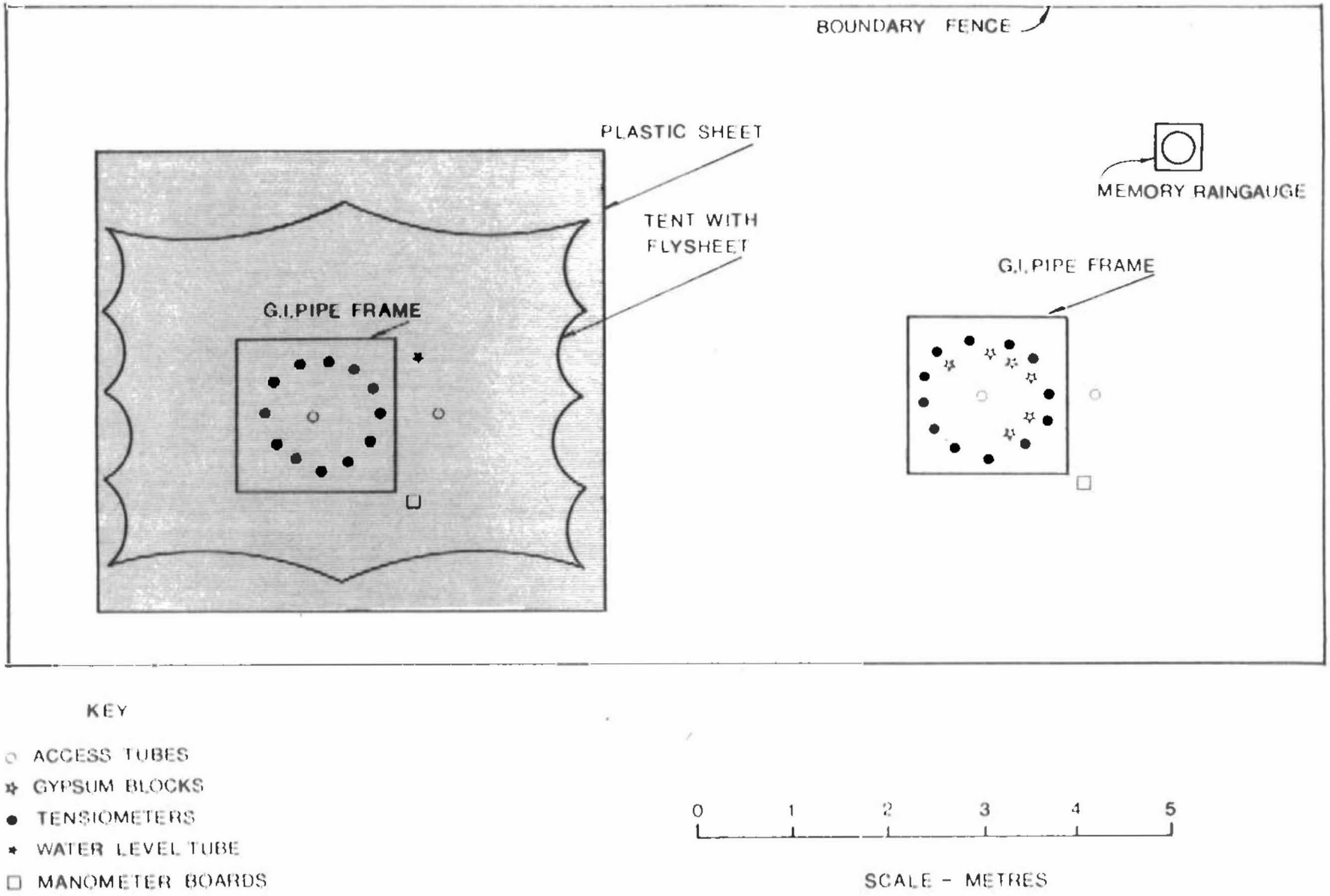

FIGURE 2 Layout of the experimental plots

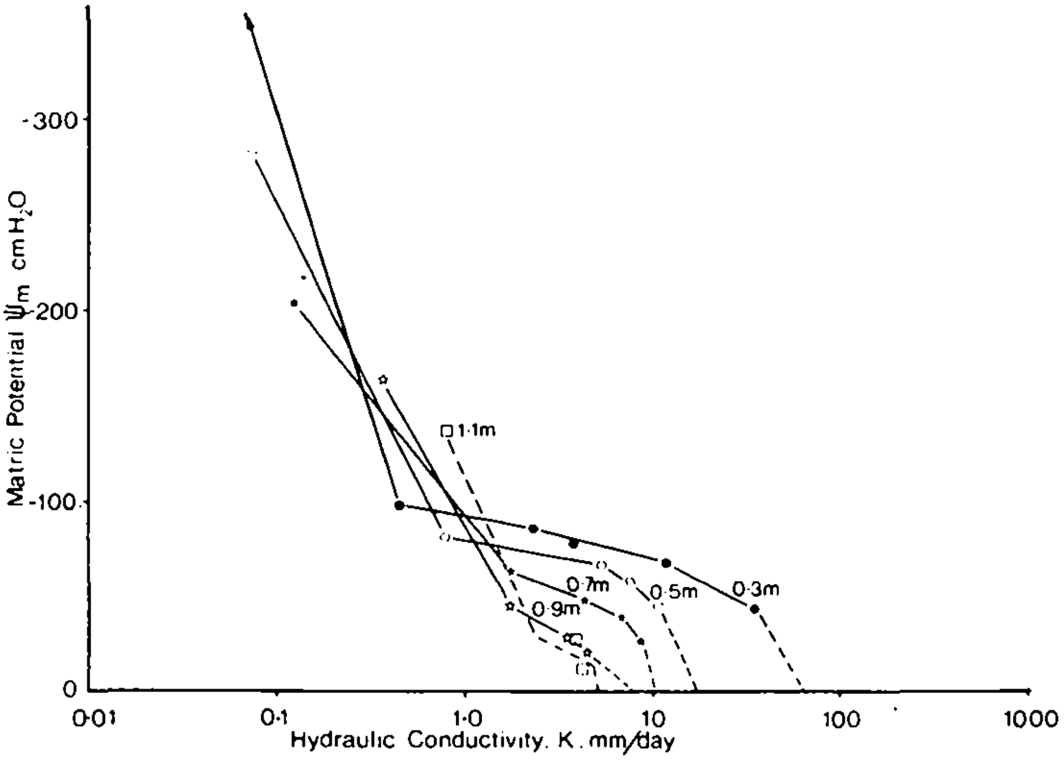

FIGURE 3 Dhaturi conductivity characteristics $K - \psi_m$

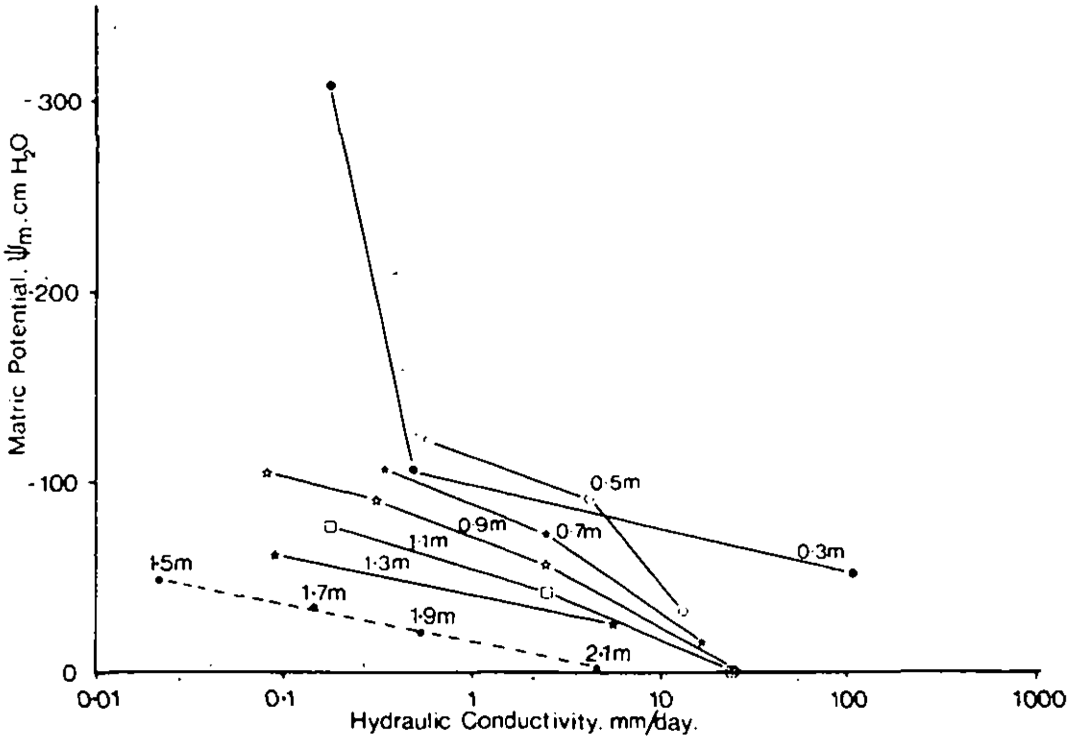

FIGURE 4 Nabibag conductivity characteristics $K - \psi_m$

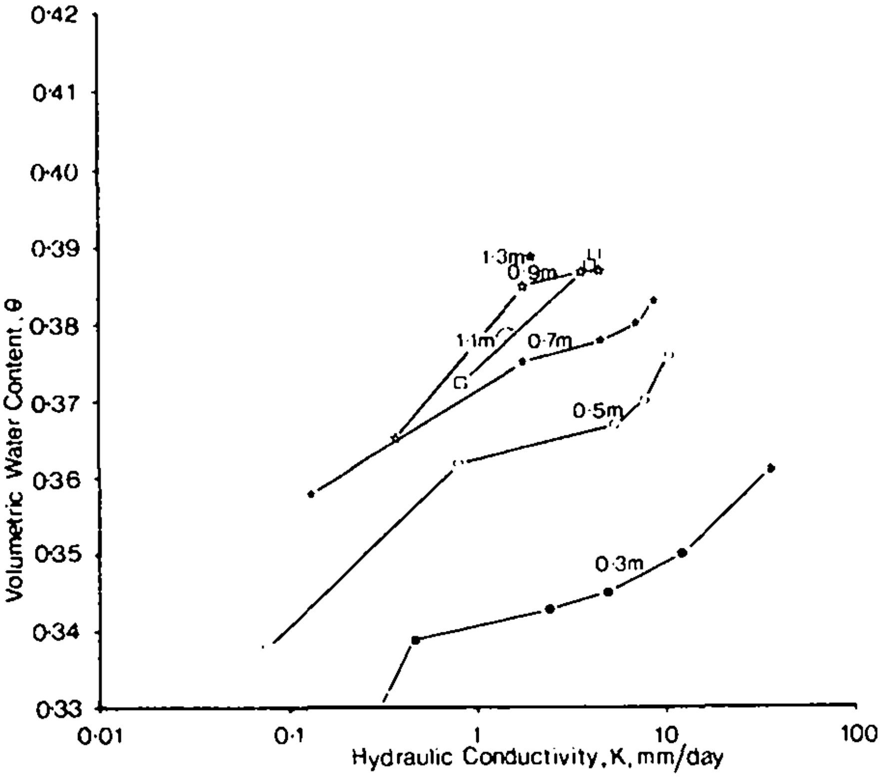

FIGURE 5 Dhaturi conductivity characteristics K - θ

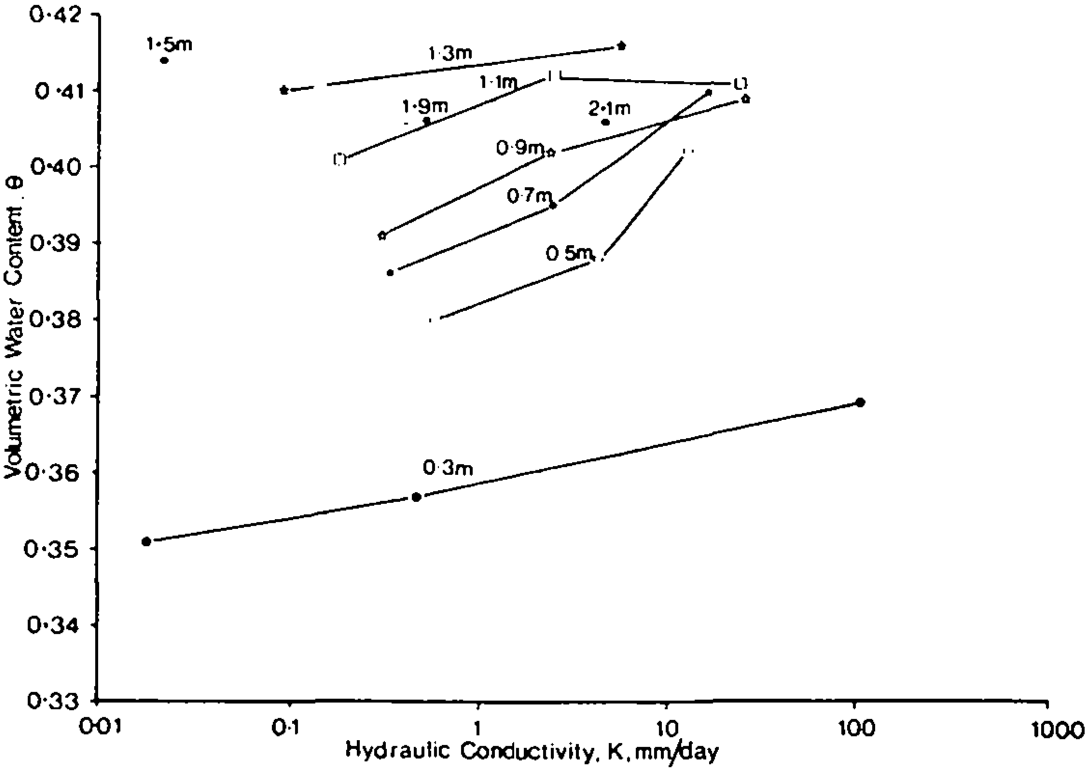

FIGURE 6 Nabibag conductivity characteristics K - θ

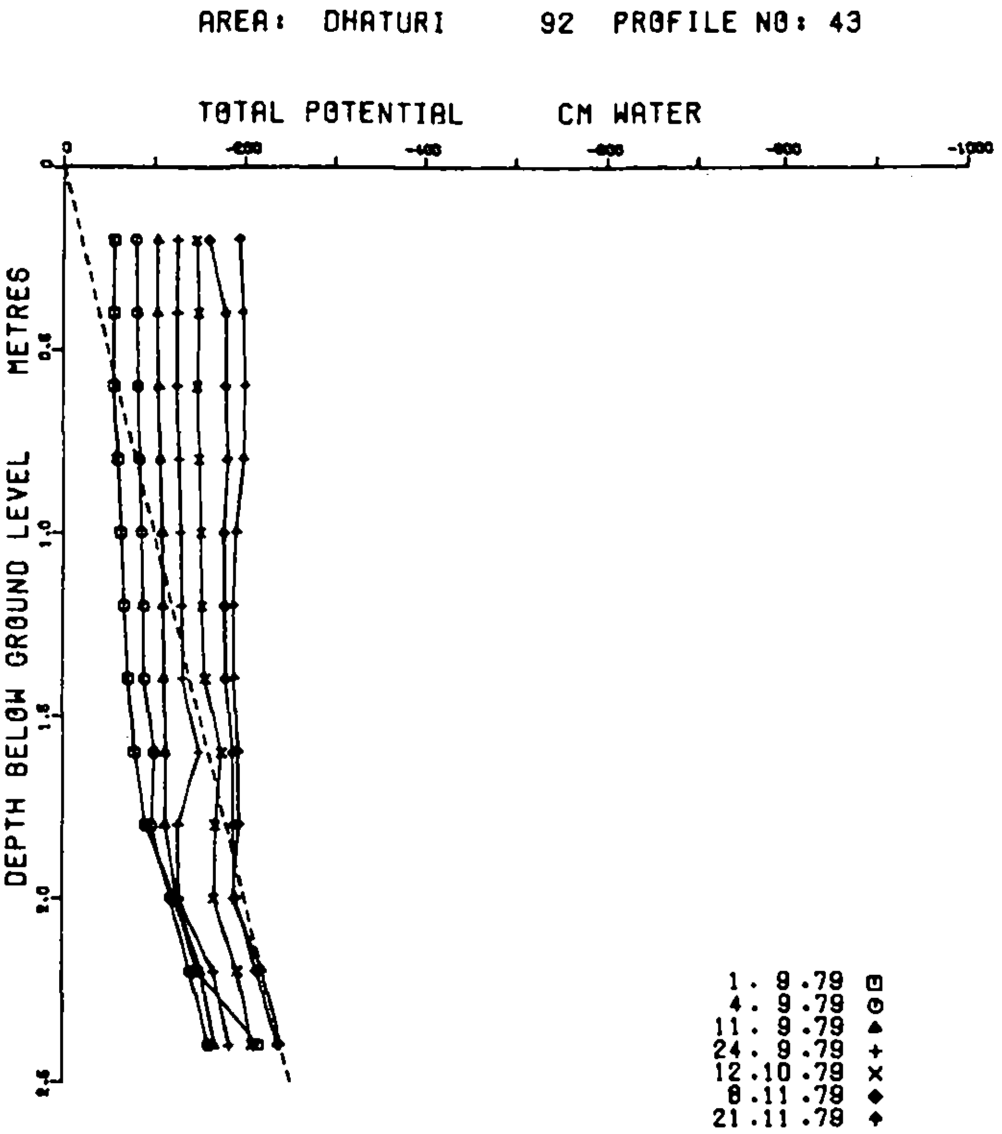

FIGURE 7 Potential profiles from Dhaturi covered plot

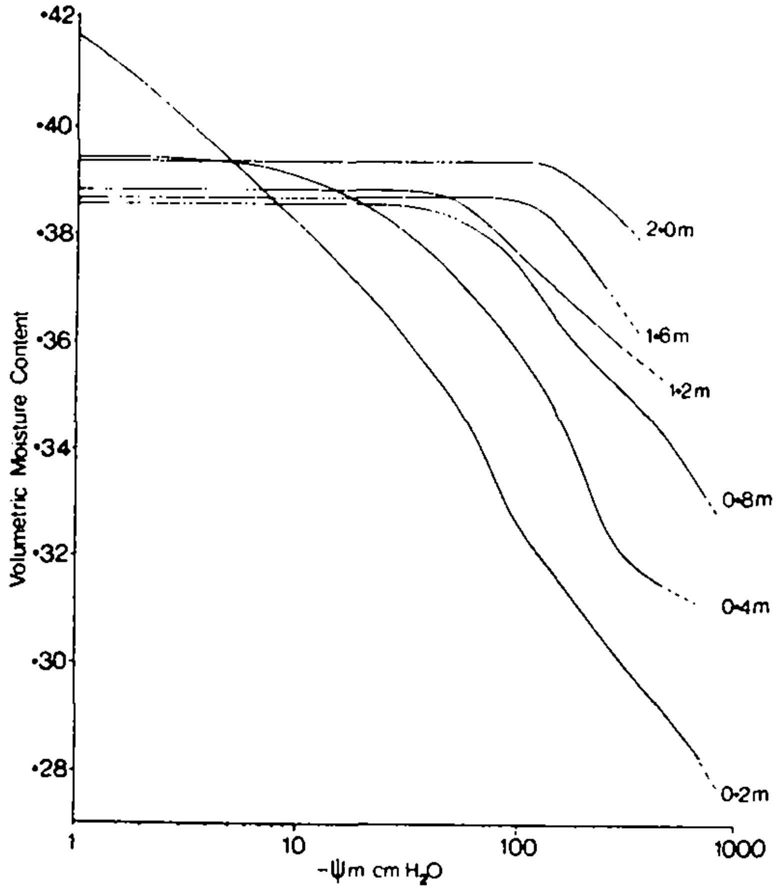

FIGURE 8

Dhaturi moisture characteristic curves

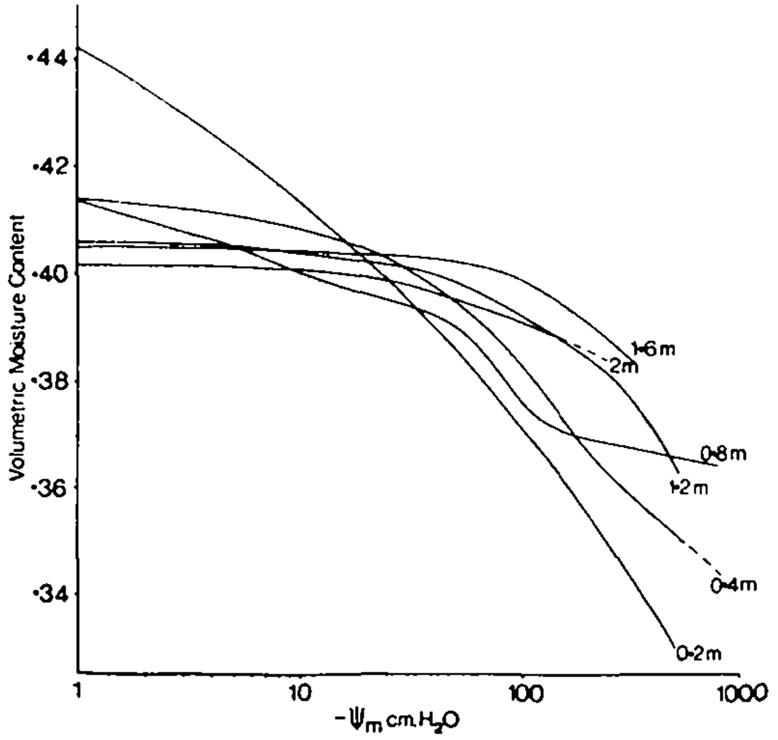

FIGURE 9 Nabibag moisture characteristic curves

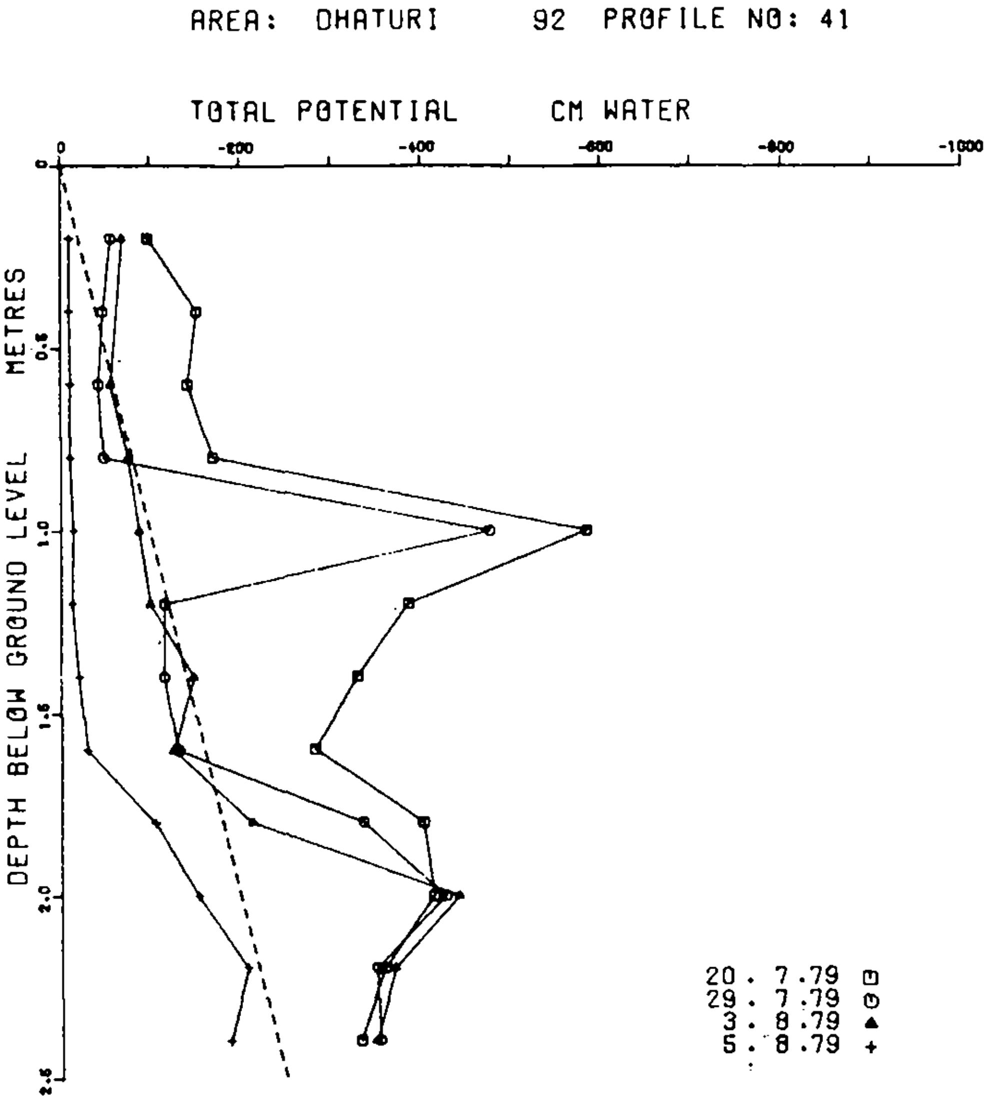

FIGURE 10 Potential profiles, illustrating wetting process. Dhaturi plot 1 (open) 1979

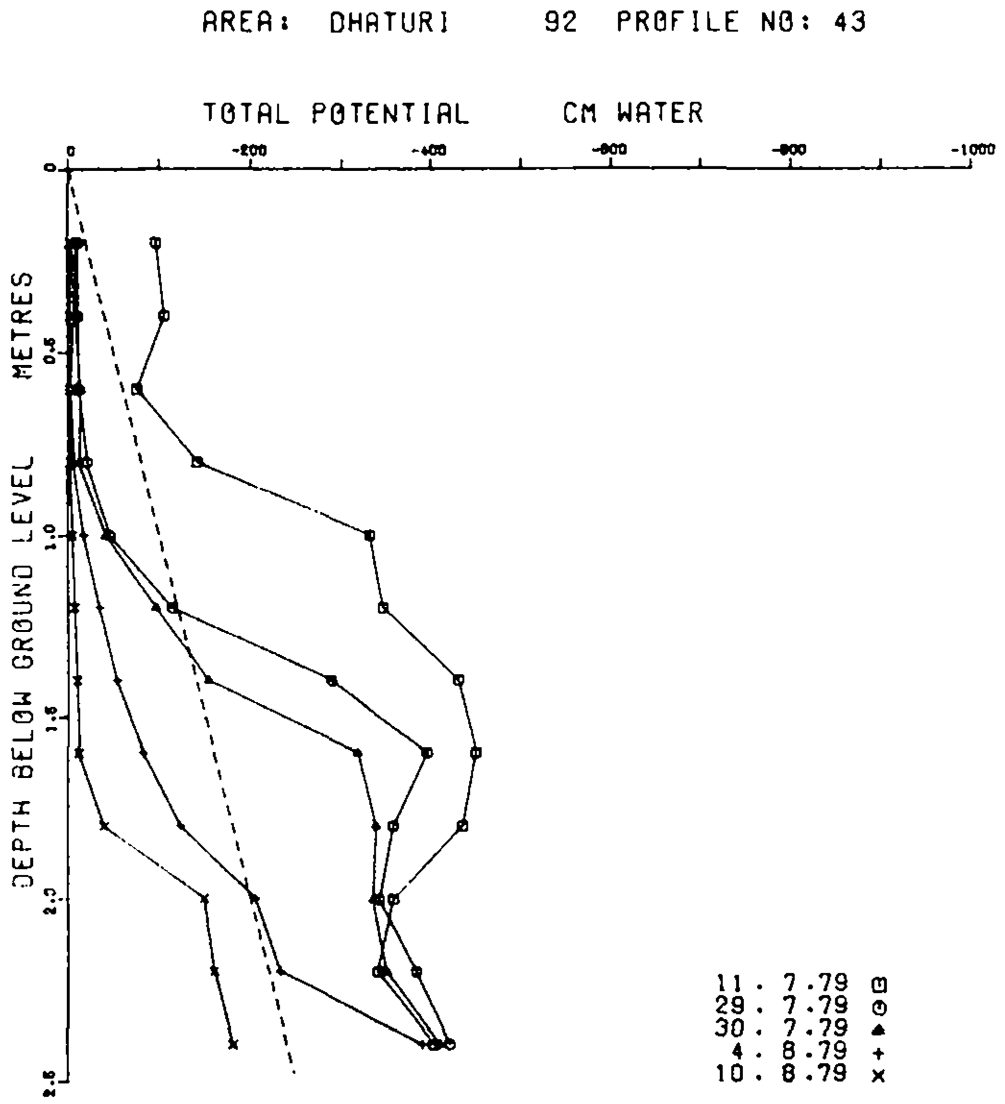

FIGURE 11 Potential profiles illustrating wetting process.
Dhaturi plot 2 (open) 1979

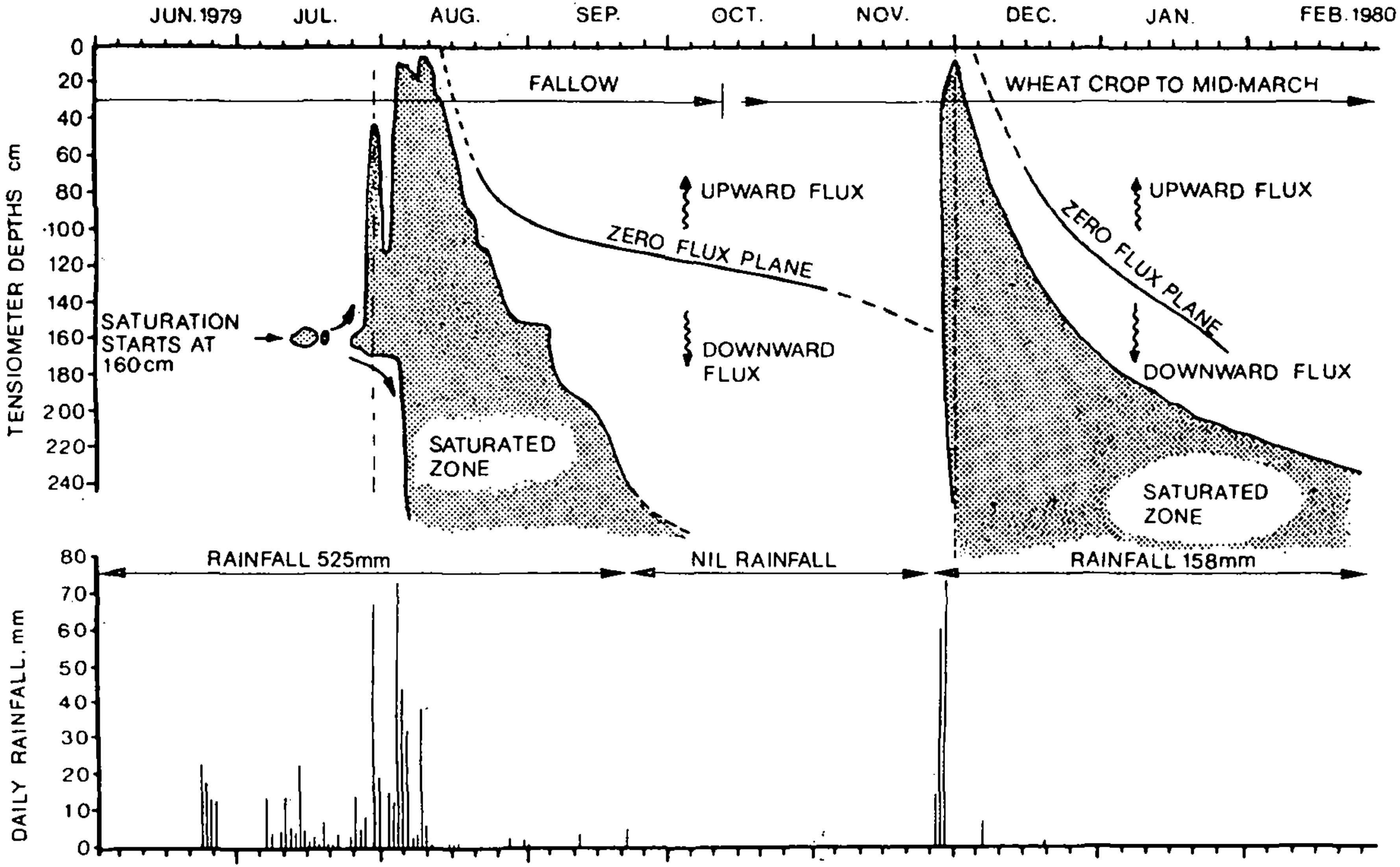

FIGURE 12 The soil water regime at Dhaturi 1979-80

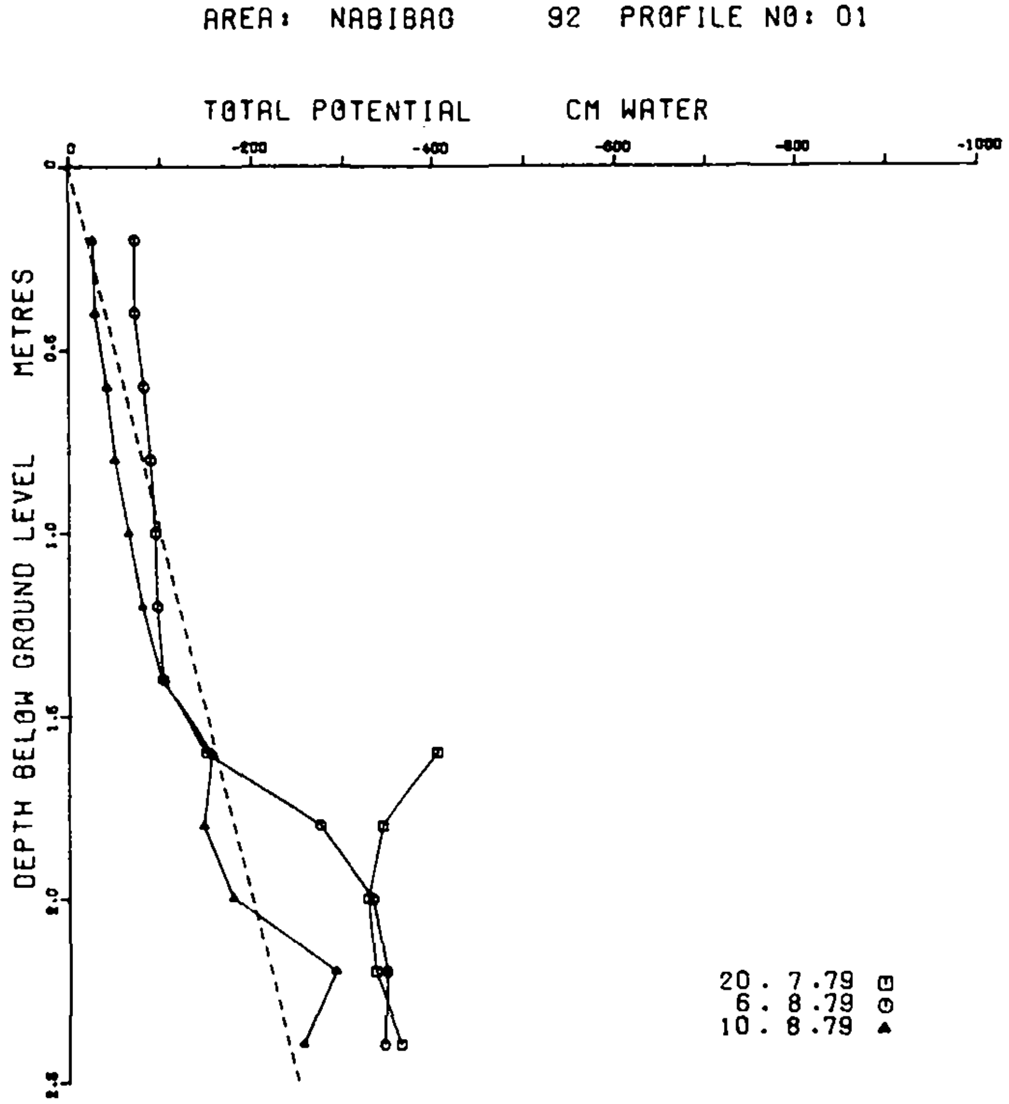

FIGURE 13 Potential profiles illustrating wetting process. Nabibag open plot 1979

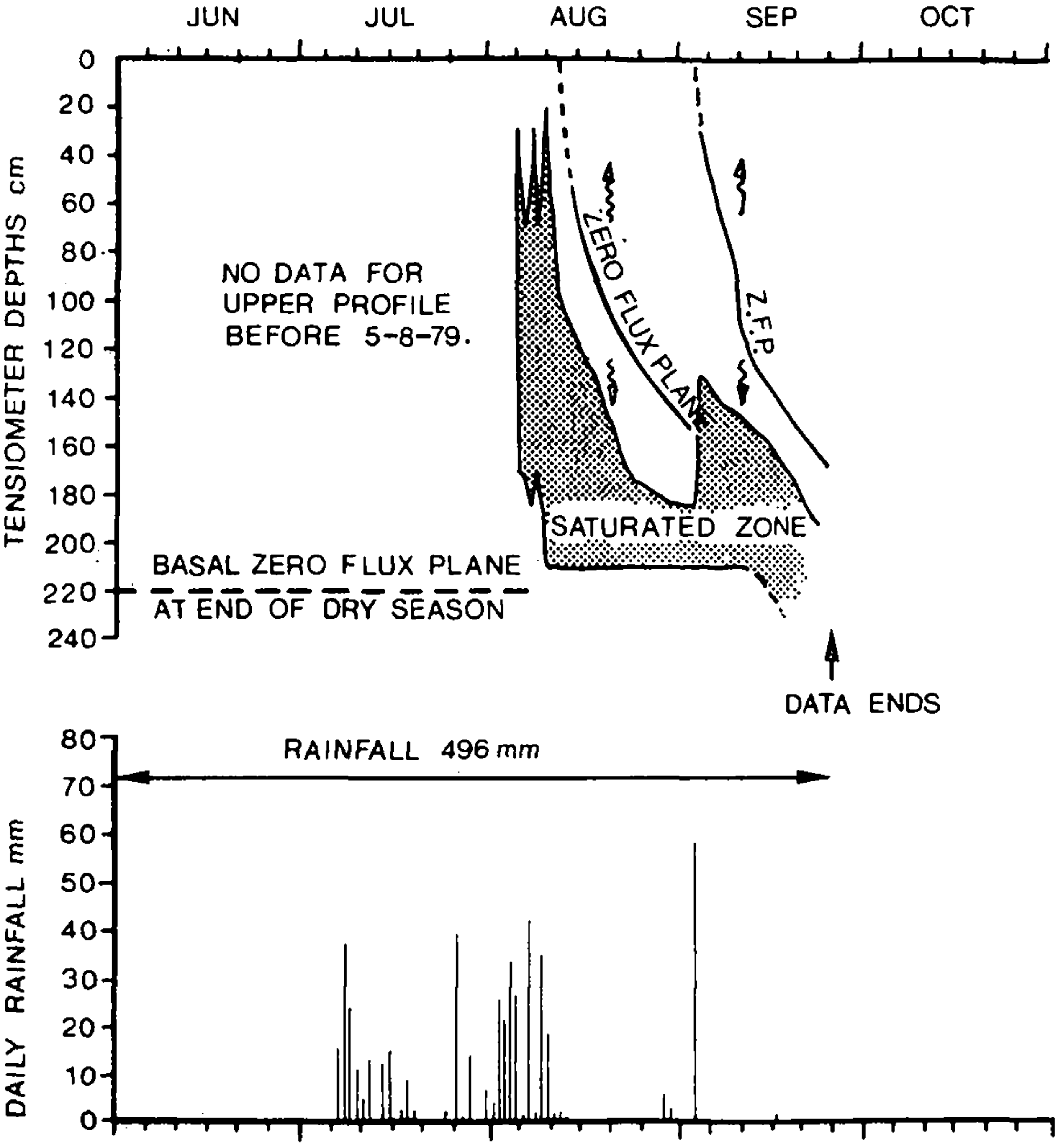

FIGURE 14 The soil water regime at Nabibag 1979

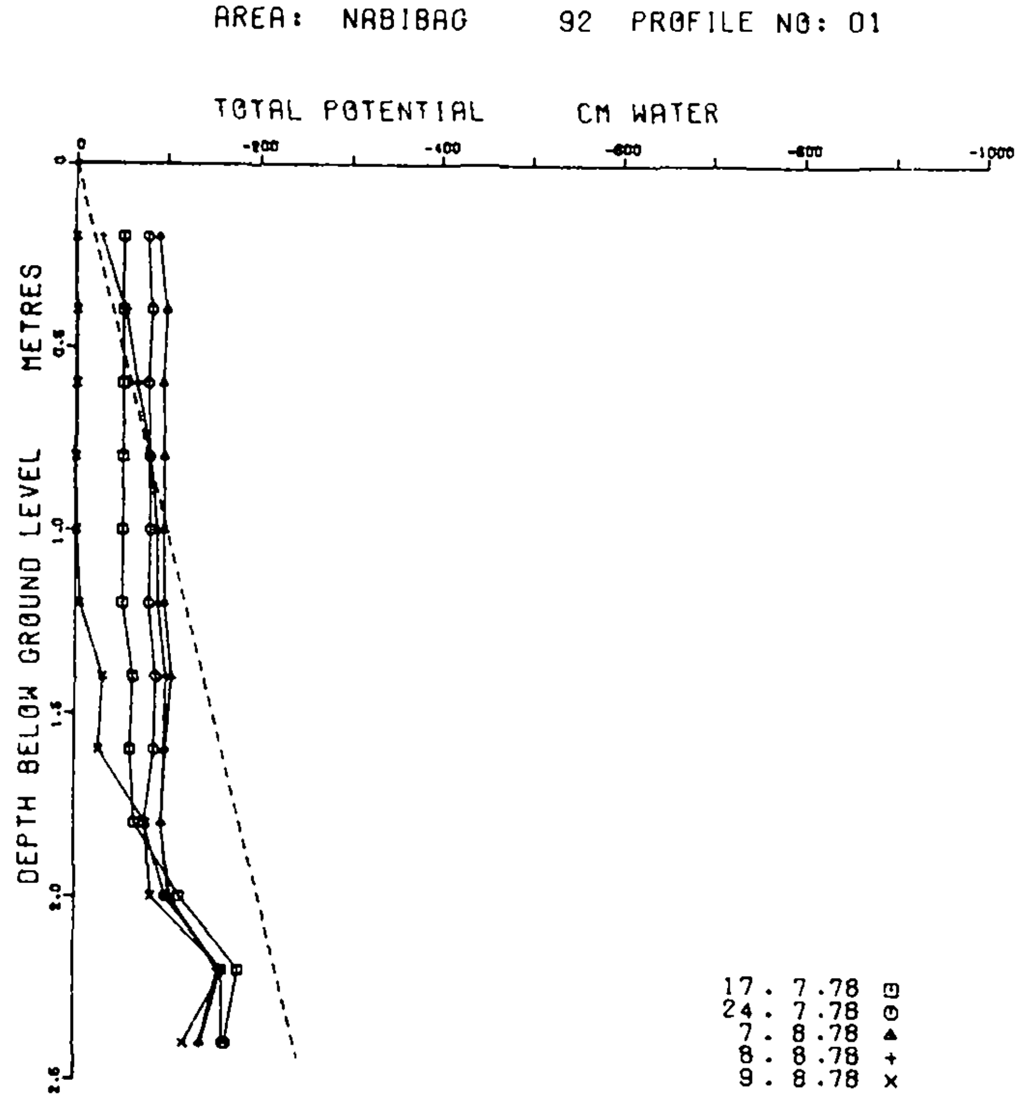

FIGURE 15 Potential profiles illustrating monsoon wetting and drying. Nabibag open plot 1978

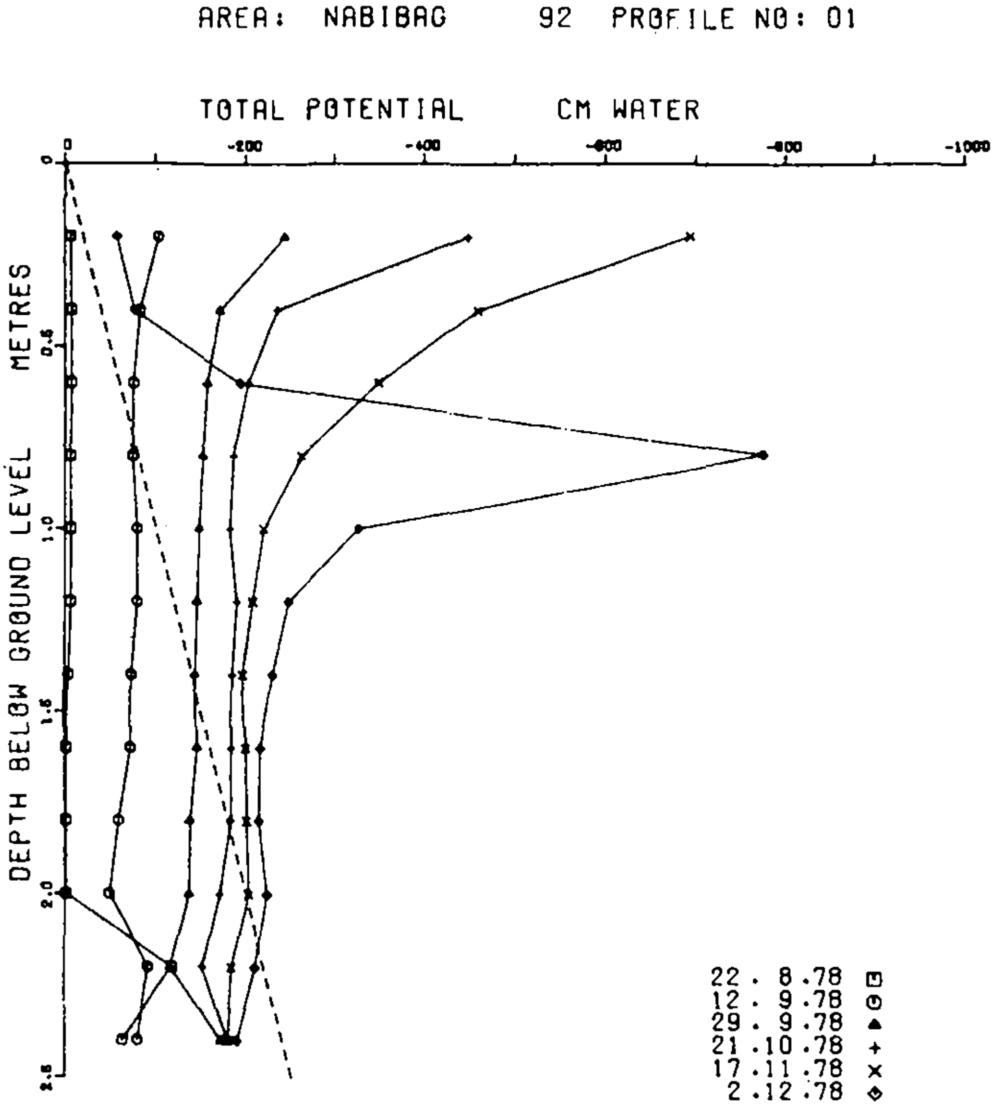

FIGURE 16 Potential profiles illustrating drying process.
Nabibag open plot 1978

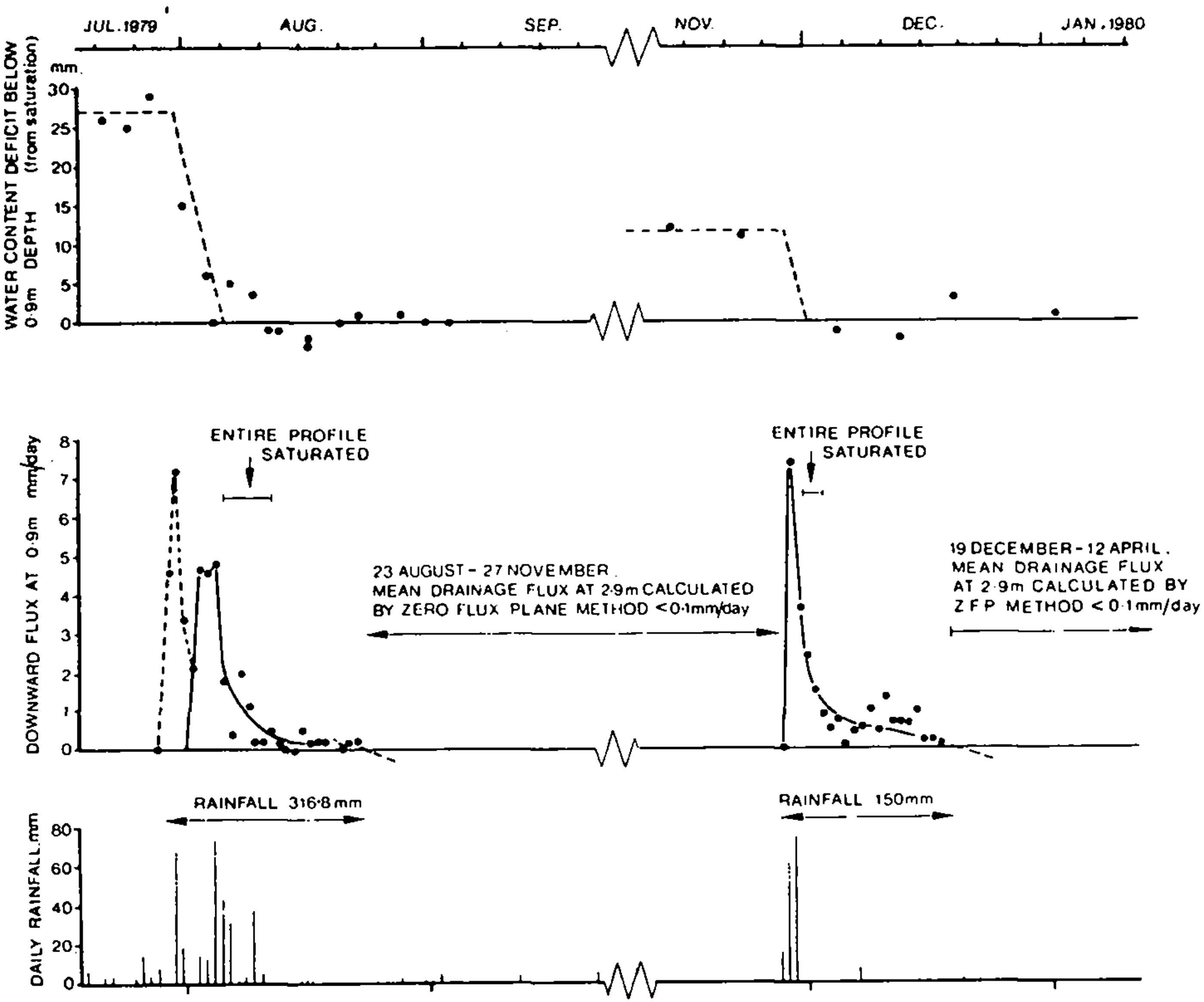

FIGURE 17 Calculated drainage fluxes at Dhaturi 1979

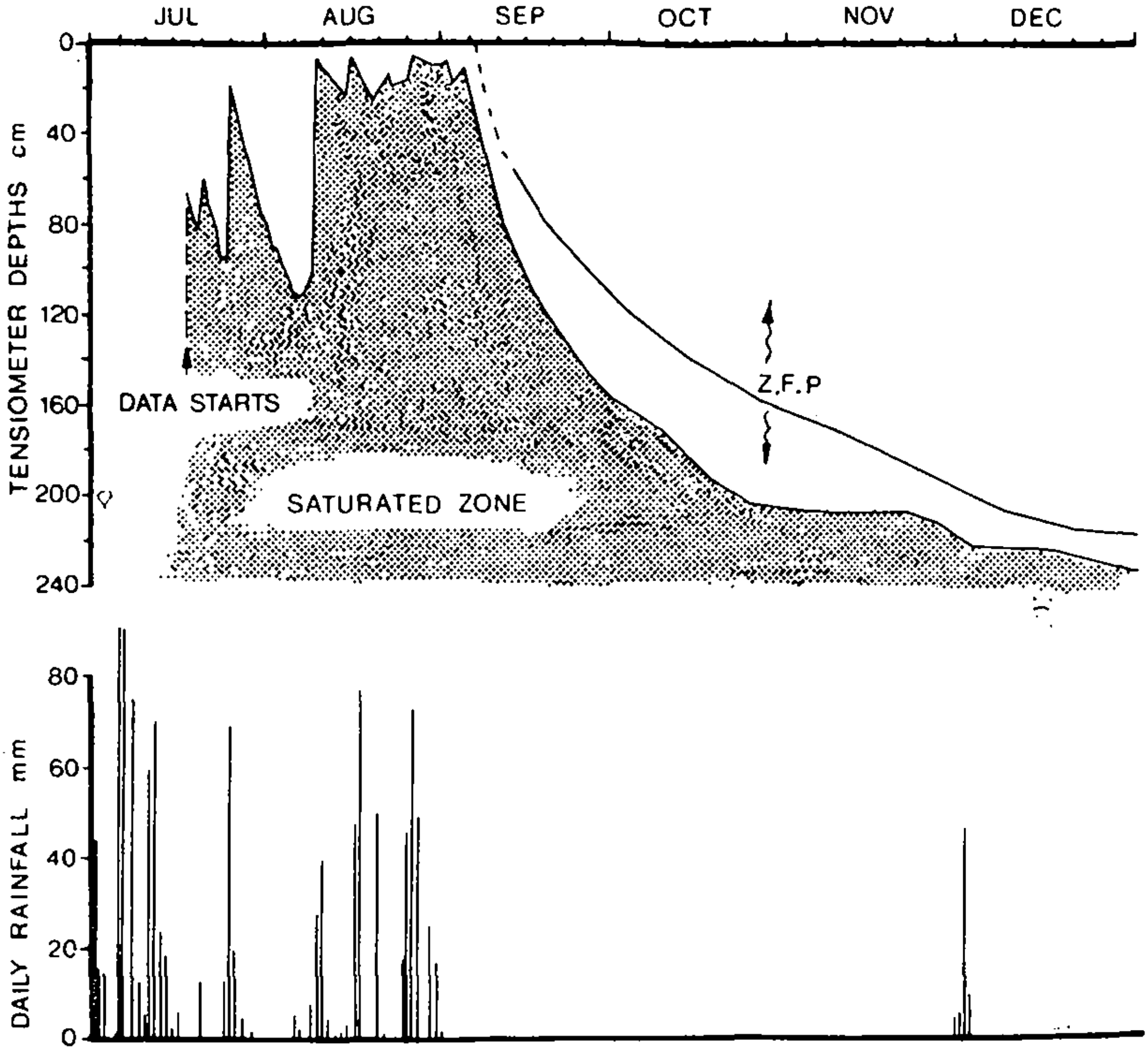

FIGURE 18 The soil water regime at Nabibag 1978

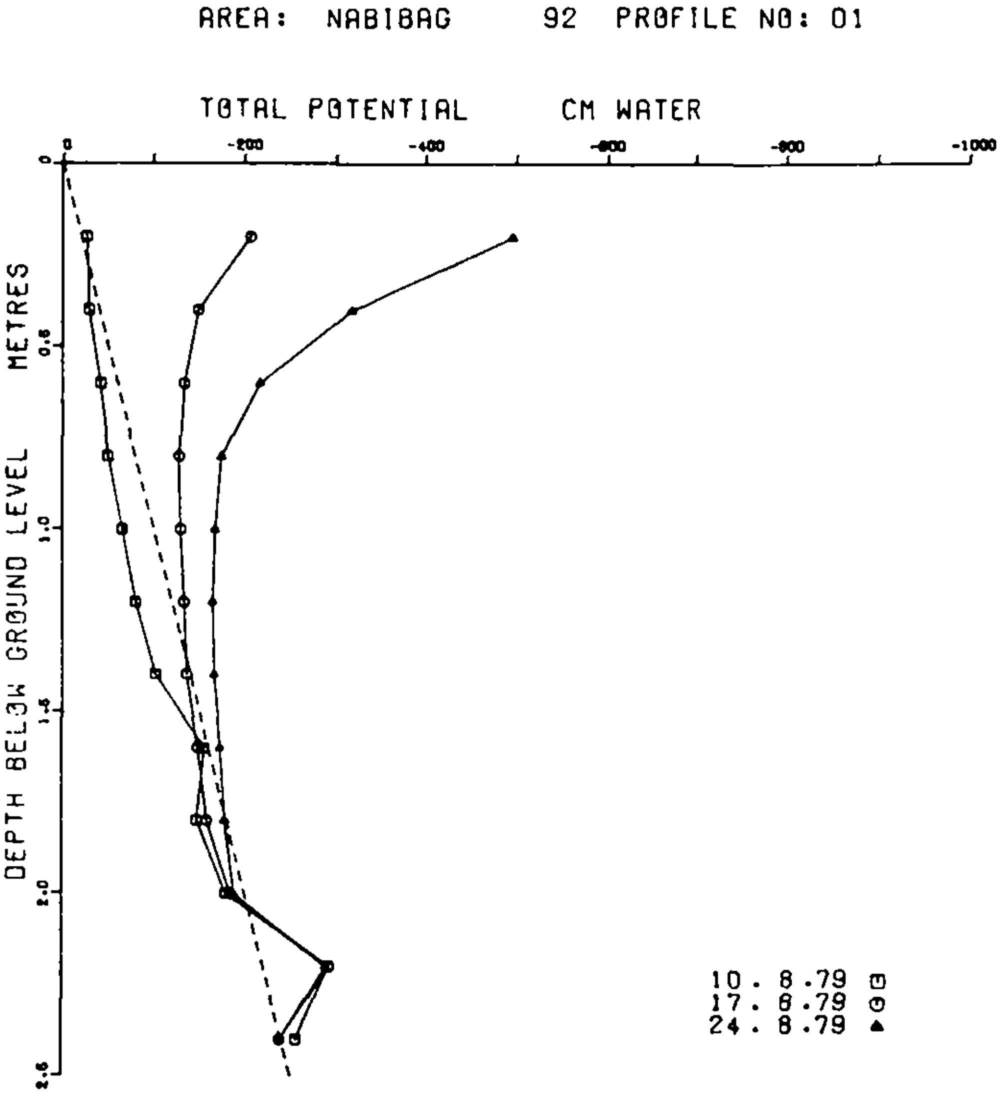

FIGURE 19 Potential profiles illustrating drying process.
Nabibag open plot 1979

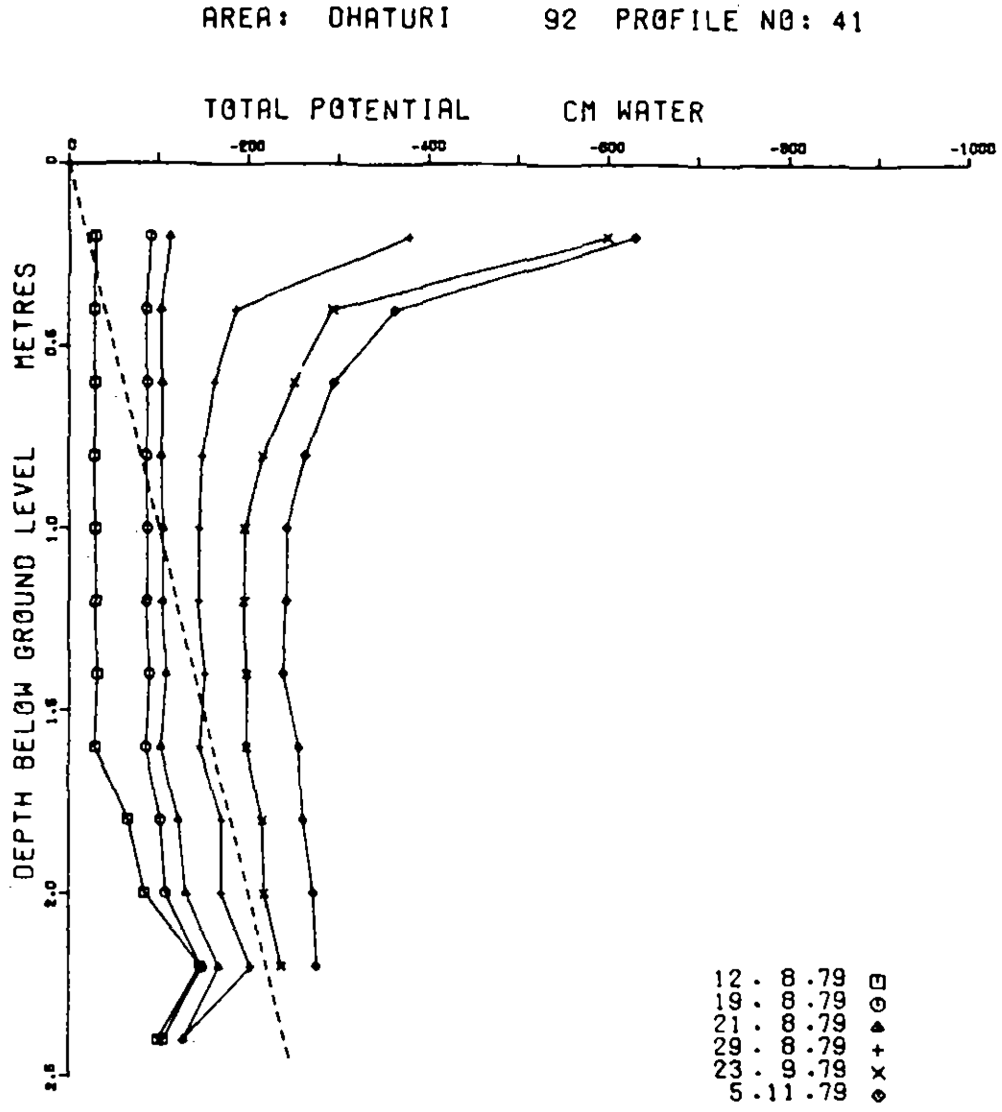

FIGURE 20 Potential profiles illustrating drying process. Dhaturi open plot 1979