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H Y D R O L O G Y

SOIL PHYSICAL PROCESSES OF GROUNDWATER  
RECHARGE THROUGH INDIAN BLACK COTTON  
SOILS

by

M G HODNETT AND J P BELL

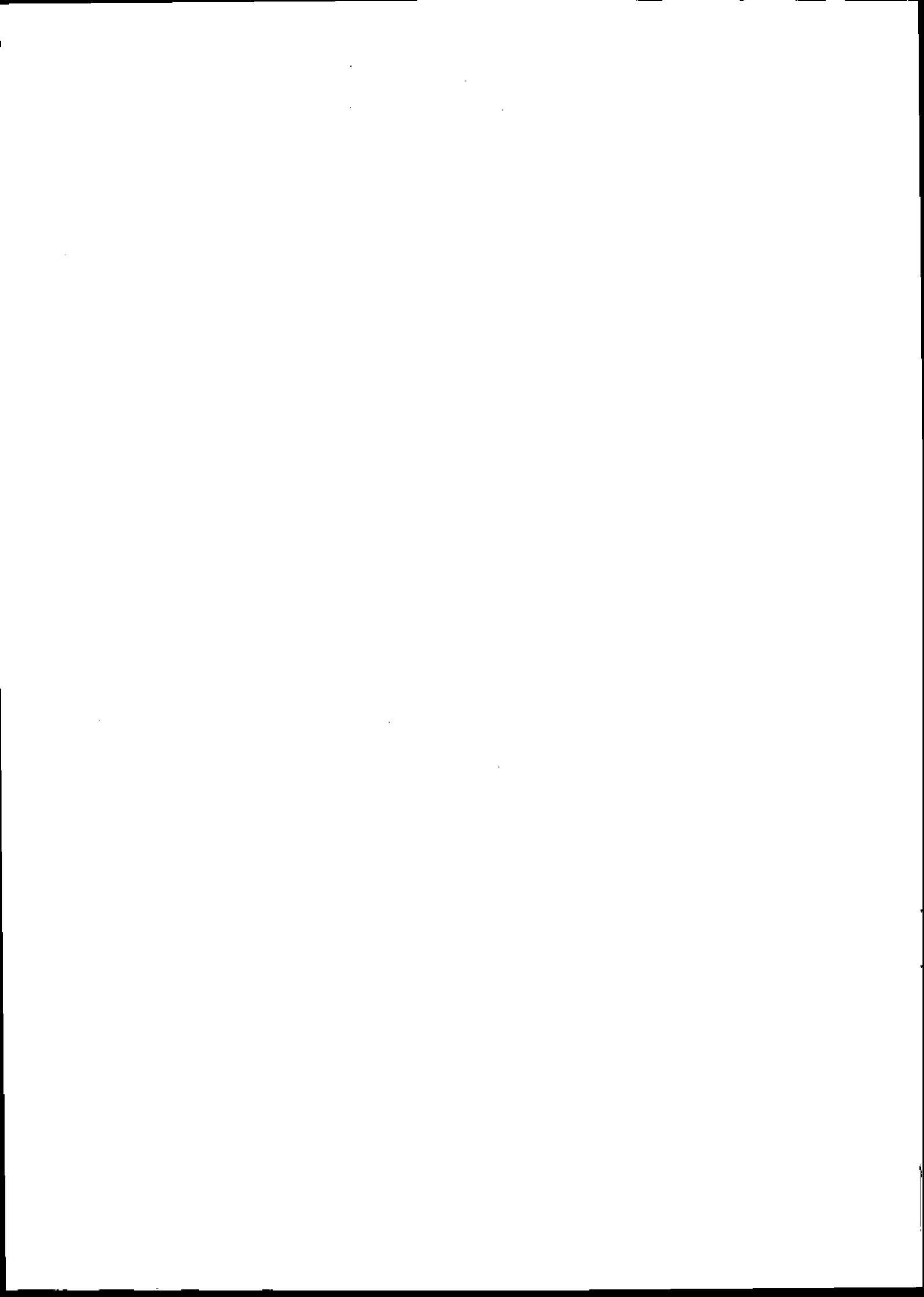
Abstract

Soil physical studies were carried out in the black cotton soil areas of the Betwa Basin, Central India, to assess their role in partitioning monsoon rainfall into runoff and groundwater recharge. The regional and annual variations of soil moisture were studied first, followed by studies of the soil water flow mechanisms at representative sites. Measurements of soil water content were made by neutron probe and soil water potential by porous pot tensiometer. Unsaturated conductivity characteristics were determined by the "instantaneous profile method" and monsoon recharge estimated by application of Darcy's Law. Dry season recharge and evaporation were calculated by the zero flux plane method. The studies suggested that significant recharge is possible only in the shallow soil areas, where structured clay/silts directly overlie the weathered basalt surface aquifer.



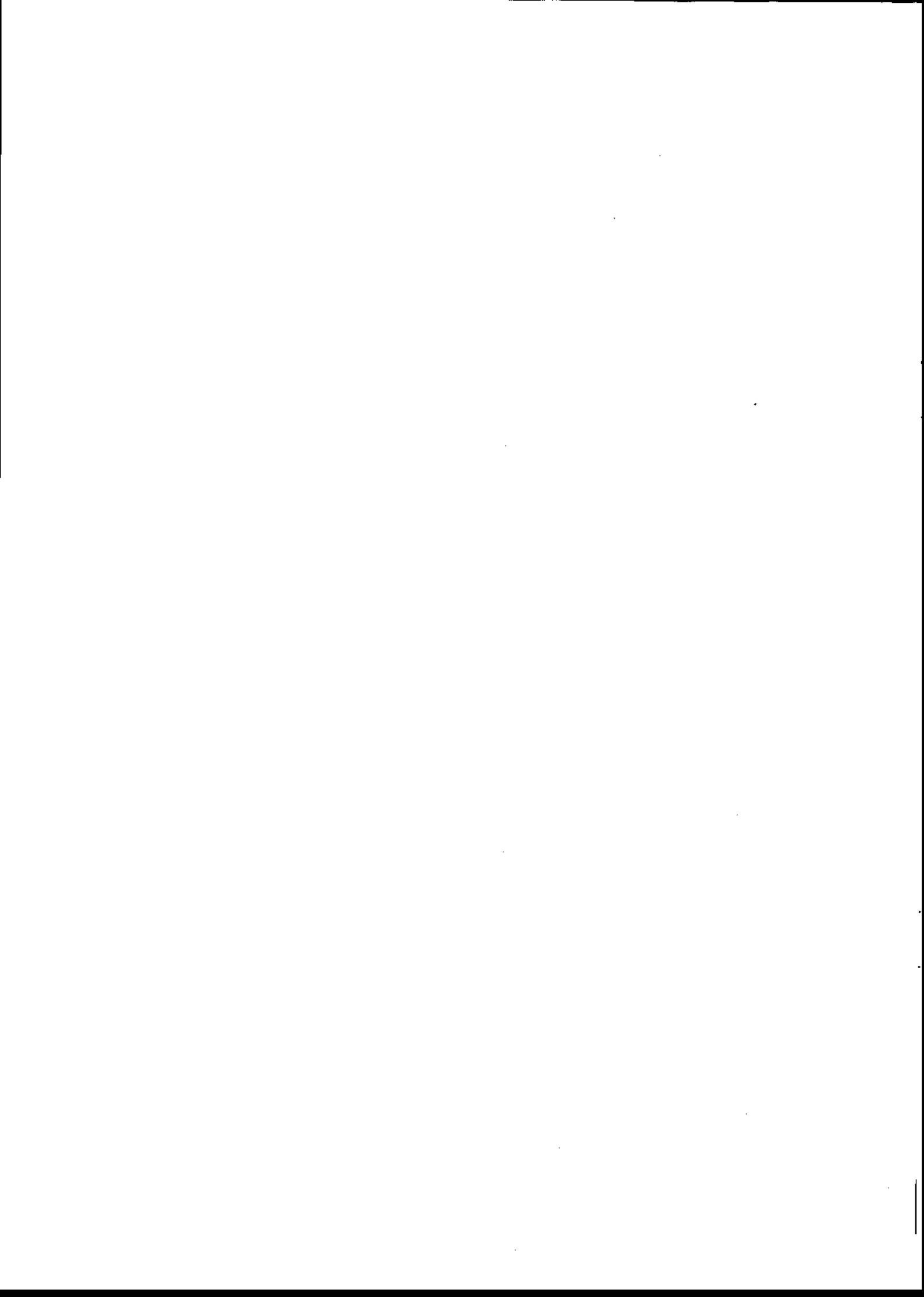
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## INTRODUCTION

The soil physical studies described here were part of a major collaborative study of the hydrogeology of the Deccan Trap basalts of the Betwa River basin above Dhukwan. The study involved the Central Groundwater Board of India, and the Institute of Geological Sciences and the Institute of Hydrology from the UK, funded by the Ministry of Overseas Development. The objectives were to assess the groundwater resources of the area, to develop a methodology for general use in the Deccan Trap areas, and to train personnel in appropriate techniques. The project was carried out between 1977 and 1980.

The importance of soil cover in determining the amounts of runoff, infiltration and aquifer recharge in a catchment area is often not fully appreciated or understood. Recharge to an unconfined aquifer has to pass through the soil before reaching the water table and the rate and amount of recharge is therefore largely governed by the hydraulic properties of the soil. The amount and timing of runoff from a catchment is also considerably influenced by the hydraulic properties of the soil, especially those of the immediate surface layer. Soil physical studies were therefore undertaken in the black cotton soils to investigate the variability of soil moisture storage and to obtain insight into the mechanisms of recharge through the soil. The studies were carried out in two separate but related phases.

The major objective of Phase I was to monitor the behaviour of the soil moisture reservoir throughout an entire year to provide 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. For this purpose the catchment was divided on the basis of topography and soil depth into soil areas which observation indicated might be hydrologically different. An extensive network of 26 neutron probe access tubes was installed covering three of the four areas initially defined: one area of shallow soils (Area I, soil depths up to 2 m) and two areas of deep soils (Areas II and III, soil depths between 2 and 12 m).

Phase II was an intensive study of the soil physical properties controlling recharge and water movement processes in the soils, carried out during the 1978 and 1979 monsoons and subsequent dry seasons. Two sites were selected for Phase II, one representing the deep soils and one the shallow soils. A third, shallow soil site was later abandoned.

Soil water content in the upper 3 m of the soil profile was measured by neutron probe. In addition, for the Phase II work, soil water potential (tension) data were obtained from mercury manometer tensiometers installed at various depths from the surface down to 2.4 m.

This report is divided into three sections:

- I The Soils
- II Areal variability of soil moisture storage
- III The influence of soil conductivity on recharge

## I THE SOILS

### General description

Black cotton soils are the major agricultural soils not only of the Betwa catchment but also of a very large proportion of the 500,000 km<sup>2</sup> of Deccan Trap basalts which cover much of the States of Madhya Pradesh, Maharashtra and Gujarat. These soils, derived from the basalts, are vertisols. They are predominantly dark coloured, silty swelling clays which have developed on a light olive brown silty clay parent material ('yellow clay') derived from the weathering of the basalts. Where the weathered basalt is within 2 m of the soil surface (Area I) the black cotton soil usually overlies the weathered basalt directly. In the deeper soil areas (Areas II and III) the combined depth of the black cotton soil and yellow clay is generally between 2 and 10 metres but may be even deeper in the central part of the catchment.

The black cotton soils show marked swelling and shrinking properties and an extensive pattern of cracks forms during the dry season. The cracks may be up to 75 mm wide at the surface, and in areas of perennial grass and scrub, may reach a depth of 6 m. Under cultivated sites, depths of 1.5 - 2 m are more typical. The soils are stone free except where they are very shallow, where pieces of weathered basalt may occur within the soil. All the basalt soils contain small concretions or 'kankar'.

Soils which are deeper than about 1.5 m are extensively cultivated and the shallower soils support a mixture of scattered cultivation, scrub jungle and forest. The proportion of scrub and forest generally increases as the soils become shallower so that forests are usually confined to the shallowest, stoniest and least cultivatable soils. The main crops of the black cotton soils are wheat, pulses (lentils and chickpeas) and linseed, which are grown in the rabi (post monsoon season). Little kharif (monsoon) cropping is practiced so that a large proportion of the cultivated area lies fallow for 7 months between the end of one rabi season (March) and the beginning of the next (October). Over most of the black cotton soil area the water table is between 2 and 11 m below ground level at the end of the dry season. It generally rises to within 0.20 m of the surface during the monsoon and for brief periods rises to the surface.

The soils developed on the outcrops of Vindhyan sandstones are normally very thin and consist of unstructured, medium to fine sand with gravel and cobbles of weathering sandstone. Although large depths of soil may occur in occasional cracks and fissures and along the sandstone/basalt contacts, soils depths elsewhere rarely exceed 0.30 m and large areas may be virtually devoid of soil cover. The sandstone derived soils are therefore unimportant in terms of soil moisture storage and support only scrub and open jungle vegetation. No studies were made of these soils.

The soils of the granite areas comprising the northern end of the Betwa catchment were not studied as this area was not considered important in the context of groundwater resources.

### Definition of soil areas

A rapid soil reconnaissance was carried out during May 1977 to define hydrologically different soil areas. Four main areas were defined, mainly on the basis of topography and soil depth. The areas were numbered I to IV and are shown in Figure 1.

### Area I

Area I covers the area along the western edge of the catchment from south of Bhopal northwards to 24° 15'N; the 450 m contour forms a convenient but approximate eastern boundary. The area is gently rolling in character and the general elevation is between 470 and 520 m above mean sea level, although occasional basalt hills exceed 550 m. Some of these hills show typical stepped trap relief, the steps marking the individual basalt flows.

The soils are mostly silty clay black cotton soils which are derived from the weathering of the basalts. Stony red lateritic soils occur on some hill tops but these give way to shallow, very dark black cotton soils where the hill slopes change from convex to concave. The depth of soil overlying the weathered basalt ranges from 0 to 2.0 metres, a typical depth being about 1.2 m. The deepest soils of Area I occur mainly in the south, extending a few kilometres north of Bhopal and also around Berasia.

The cotton soils in Area I are darker than those elsewhere in the catchment and the colour of the surface soil is darkest where the soils are shallowest. Surface soil colours (moist) range from 10 YR 3/1, very dark grey, to 10 YR 4/2, dark greyish brown on the Munsell scale. The swelling and shrinking properties of the soils appear to be more pronounced in this area than elsewhere in the catchment and cracks frequently penetrate to the weathered basalt beneath. The mean dry bulk density measured in the upper 0.6 m of the soil profiles was  $1.381 \pm 0.110 \text{ gm cm}^{-3}$  with a range from 1.149 to  $1.547 \text{ gm cm}^{-3}$ . The lowest bulk densities occurred in the shallowest soils.

About 60% of the area is cultivated, the remainder being scrub jungle and rough grazing. The lateritic soils and the very shallow black cotton soils support only scrub jungle but where the soil is slightly deeper the scrub is interspersed with the areas of cultivation. The deeper soils are extensively cultivated. Pulses are the main crop, followed by wheat and linseed. About 10% of Area I is used for kharif (monsoon) season crops, mainly jowar (millet), maize and groundnuts, and an estimated 5% of the area is irrigated from river abstraction and dug wells. Large scale irrigation is largely restricted to areas where mains power is available for electric pump sets i.e. mainly close to Bhopal.

### Area II

Area II extends from Area I eastwards to the Betwa and also includes the basalt floored valleys in the Vindhyan sandstone hills between Bhopal and Vidisha. Drainage is towards the east as in Area I and the area is very flat and open, with broad shallow valleys and wide low interfluves. Apart from occasional sandstone inliers there are no hills and the general elevation of the area is between 410 and 460 metres above mean sea level. Slopes rarely exceed 3% and are typically less than 1%.

In Area II the depth to the weathered basalt ranges from 2 m to more than 10 m and is rarely less than 3 m. The surface soil colour is areally very uniform, typically 2.5Y 4/2, dark greyish brown and the colour is uniform throughout the upper 2 m of the profile. Below this depth the colour becomes gradually paler, changing typically to 2.5Y 5/3, light olive brown ("yellow clay"). There is no apparent textural change with depth.

The dry bulk density of the upper 0.60 m of the profile is areally very uniform, the mean value being  $1.527 \pm 0.024 \text{ gm cm}^{-3}$ . Bulk densities are higher and less variable than in Area I.

Approximately 85% of Area II is cultivated and there are few trees. The uncultivated areas are generally covered with rough grass and scrub and are found as narrow strips along field boundaries, tracks and stream beds and occasionally in larger blocks. The grass/scrub areas are important agronomically, providing grazing and hay for cattle and buffalo. The major crops are the same as in Area I but wheat is more important than pulses.

The approximate proportions of the cultivated area covered by different crops are wheat 60%, pulses 30% and linseed 10%. Only about 2% of the area is irrigated.

### Area III

Area III covers the area from the Betwa eastwards to the ridge of forested basalt hills running northwards from near Dehgaon to beyond Gyaraspur and includes the Nion, Keothan, Narain and lower Bina sub-catchments.

The topography, elevation, soils and land use are very similar to those of Area II but the drainage is towards the north and there are more sandstone inliers. These are concentrated mainly in the western Nion basin. There are also a few isolated basalt hills in the north.

The dry bulk densities of the soils of this area are also very uniform, the mean being  $1.548 \pm 0.042 \text{ gm cm}^{-3}$ . This is not significantly different to the mean bulk density in Area II.

### Area IV

Area IV consists of the upper Bina and Babnai catchments, which lie in the eastern most part of the Betwa catchment. The area is bordered in the west, south and east by forested basalt hills with rubbly shallow soils and its general elevation is 520-580 metres. This area is more dissected and slopes are generally slightly steeper than in Areas II and III.

The soils are similar in colour and texture to those of Areas II and III but are shallower, the depth to the weathered basalt ranging from 2-4 m. Approximately 70% of the area is cultivated.

## II AREAL VARIABILITY OF SOIL MOISTURE STORAGE

### The neutron probe access tube network

Eight access tubes were installed in cropped land in each of Areas I, II and III during September 1977. One additional access tube was installed in Area I in March 1978 and a second was installed in Area III in May; these were sited in grass/scrub, close to tubes in cultivated land.

The sites were distributed among the main crops in each area in approximate proportion of the area under each rabi crop and sites were widely spread to take account of areal variations of soil characteristics within each area. In Area I sites were also distributed with regard to different depths of soil. Tubes

were sited at least 4 m from crop boundaries to avoid edge effects and generally between 15 and 40 metres from the roads to avoid interference by passers-by. The locations of the 26 sites are shown in Figure 1.

Water content observations were made down each access tube at approximately weekly intervals using an Institute of Hydrology neutron probe. Readings were taken at 0.20 metre depth intervals from 0.20 m below the surface down to the bottom of the tube. Observations during the monsoon period were erratic because access to parts of the area was restricted by flooding.

No access tubes were installed in Area IV since the crop had been sown before access tubes could be installed. Any installation work would have severely damaged the germinating crops and rendered the sites unrepresentative.

#### Neutron probe calibration

The calibration procedure detailed by Bell (1976) was used. Twenty-five pairs of moisture content and count rate data were obtained from 18 sites in the catchment at depths between 0.30 and 0.65 m. The calibration equation which was derived for the black cotton soils was:

$$\theta = 0.818 \frac{R}{R_s} - 0.011$$

where  $\theta$  is volumetric moisture content (moisture volume fraction)  
 $R$  is the neutron probe count rate measured in soil  
 $R_s$  is the count rate measured in a water standard

The calibration line data points are shown in Figure 2 and the lack of scatter is immediately apparent; the correlation coefficient was 0.983. This shows that there is little difference in the soil characteristics of the different areas and suggests that the calibration could also be applied to similar soils outside the catchment.

#### Discussion of the results of Phase I.

##### Spatial Variability

The soils in Area I vary in depth from the feather edges adjoining the lateritic basalt outcrops near the western boundary of the catchment, to 2 m. The access tube network represented a variety of depths within this range. Figure 3 (a) shows wettest and driest recorded profiles for a typical intermediate depth, with hard, partially weathered basalt below 1.2 m. Figure 3 (b) shows a similar soil profile but with soft, well weathered basalt below 1.4 m, merging into hard weathered basalt at about 2.5 m. The separation of the two profiles below 1.4 m is due to the soft weathered basalt which, being coarse textured, can lose a relatively large amount of water by drainage as the water table falls through it; this represents the relatively high specific yield of the soft weathered basalt. Many of the profiles in Area I contain some weathered basalt and this contributes to a greater variability of soil moisture within the measured profiles than is the case in Areas II and III.

There is also considerable variability below 1 m between profiles. This is well illustrated in Figure 4 which shows the mean wettest and mean driest recorded profiles within each area, together with an envelope defining one standard deviation. A marked contrast is seen between Area I and Areas II and III. It is also

the monsoon and do not start to abstract and transpire much water until some weeks after sowing in October.

### Soil moisture replenishment

Initial replenishment of soil moisture at the beginning of the monsoon is very variable between sites. For example, data from the Nion subcatchment for June 1978 show that there were very considerable differences between the storage increases at the different sites when compared to the mean rainfall. In the period from 2 to 16 June, the mean rainfall was 46.4 mm and the storage changes ranged from -3.4 to +98.7 mm. For the period from 2 to 23 June the mean rainfall was 119.7 mm and the storage changes ranged from 50.6 to 516.5 mm (Figure 5).

These differences may arise from a combination of two reasons:

- 1 The rainfall is very variable over the area. Between 2 and 23 June there was 236.5 mm of rain at Vidisha, 125.6 mm at Gyaspur and 58.8 mm at Sarsoda. This apparent east to west trend of increasing rainfall was not reflected by the storage data at this time (c.f. February rainfall).
- 2 Infiltration of water into the soil has a considerable small scale variability. This is clearly shown by the tenfold differences between the increases in storage at the cultivated site III<sub>1</sub> and the grass and scrub site III<sub>1A</sub>, which are only 15 metres apart. The profile was fully wetted to a depth of 3 metres at site III<sub>1A</sub>, but to only 0.30 m at site III<sub>1</sub>. The reason for this is that during the early part of the monsoon much of the soil surface becomes relatively 'sealed' by the compacting action of raindrops. Small cracks may be bridged by the swelling of the surface soil so that the water runs off these areas and into depressions or large cracks which have remained open. The cracks which receive this local runoff may have relatively large 'catchments' so that in small pockets, such as site III<sub>1A</sub>, the infiltration can exceed the rainfall by many times. The results from these two sites illustrate the importance of the cracks to the process of soil moisture replenishment at the beginning of the monsoon.

The annual cycle of soil moisture storage for Areas II and III is shown in Figure 6. In the 1978 monsoon more than 90% of the soil moisture storage in the deep soil areas was replenished within a month of the start of the monsoon, after only 480 mm (45%) of the average monsoon rainfall had fallen. In the shallow soil area a greater amount of rainfall (638 mm) was required to replenish 90% of the storage, largely because of the greater amount of storage within the weathered basalt below the measured profiles. In Area I the initial rate of post monsoon depletion was greater than for Areas II and III. This different behaviour of Area I at the end of the monsoon is also attributable to the variable thickness of weathered basalt in the measured profiles. The weathered basalt has a specific yield of 5%-10% compared with the black cotton soil (1-2%) and the yellow clay (< 0.5%), and drains more readily.

The network mean storage in the wettest state for Areas II and III was almost identical in 1978 and 1979, the difference being less than 3 mm. It may therefore be concluded that even in rainfall deficient monsoons (like 1979) the soil moisture will be replenished entirely.

### Drainage and Evaporation

Post-monsoon drainage losses from the deep soils are small. During the 1977-78 dry season only 10% (28 mm) of the moisture loss from the upper 2.5 m was by drainage (see page 15).

evident that the soils of Area I become wetter in the top metre than in the other areas, the mean moisture volume fractions being 0.437, 0.416 and 0.412 for Areas I, II and III respectively. The profiles in Areas II and III were generally measured down to 3.2 m, the length of the access tube installation equipment available. The upper 2.0-2.5 m of this can be regarded as black cotton soil while the material below is the clay-silt (yellow clay) parent material which is generally absent in soil Area I. The remarkable similarity between the mean wettest and mean driest profiles for Areas II and III (Figure 4) clearly demonstrates the uniformity of the soil across the 60 km transect.

#### Soil moisture depletion in the dry season

The depletion of soil moisture in the dry season is defined here as the total deficit which accumulated in the upper 2.5 m of the profile with respect to the wettest state (in Area I the depletion, D, is quoted to the base of the measured profile, which varies in depth from site to site). Depletion represents the sum of evaporation E and drainage d (the latter being very small) and includes rainfall, P i.e.

$$D = E + d - P$$

Rainfall in the winter is very localised and the mean rainfall determined by the raingauge network bears very little relation to the rainfall received at the various access tube sites (which was not measured). Hence, the variability of soil moisture depletion between sites is probably as much a reflection of rainfall variability as of crop water use. This is well illustrated by the following example. Between the 7 and 17 February, 1978, 12.9 mm of rainfall were recorded at Vidisha, a few kilometres west of the Nion catchment, 112.4 mm at Gyrapur, at the southern end of the Keothan catchment, and 27.2 mm at Sarsoda at the southern end of the Nion catchment. The west to east trend of increasing rainfall was clearly reflected in the soil moisture storage increases at the access tube sites between 4 and 17 February 1978.

	West				East			
Site No: all in Area III	1	2	3	4	5	6	7	8
Storage increase mm:	0.9	3.8	3.8	20.8	37.2	58.8	34.4	73.6

In Areas II and III the mean depletion in 1977/78 for the cultivated sites was 233 mm, ranging between 161 mm and 333 mm. The mean in Area I was 230 mm, ranging between 190 and 298 mm. While the depletion was therefore similar in quantity in all areas, the distribution of depletion with depth was very different; as can be seen in Figure 4 the depth of abstraction was less in Area I but the soil was more dried out. The mean depletion at eight wheat sites was 239 mm with a standard deviation of 54 mm, while at three 'dal' sites it was 223 mm with a standard deviation of 28 mm. This difference is not statistically different and thus it may be concluded that crop type has little effect on overall depletion.

However, there was a marked difference under the permanent grass/scrub represented by site III<sub>1A</sub> (Figure 3d). The depletion here was 508 mm, extending down to 3.0 m, with some additional depletion below this which could not be measured. At the adjacent cropped site III<sub>1</sub> (Figure 3c), the depletion was only 233 mm and was confined to the upper 2.5 m. This greater depletion beneath the grass/scrub occurs because the vegetation is permanent and is able to transpire at the potential rate during and immediately after the monsoon. The cropped areas are fallow during

Actual daily mean evaporation rates calculated from the water balance for the Nion subcatchment for the three periods 2 to 8 September, 8 to 21 September (both 1978) and 7 to 28 October (1977) were 4.1 (2.9), 1.9 (4.9) and 0.6 (4.4) mm/day respectively. The figures in parentheses show the potential evaporation rates (based on a regression against daily temperature) for the same periods. These data show that the evaporation rate from the fallow soil may exceed potential when the soils are very wet, but that the rate drops rapidly at 40% of potential within 3 weeks and to only 14% of potential after a further 3 weeks.

The total actual evaporation from the cropped sites calculated from the water balance for the bulk of the depletion period from 14 October, 1977 to 2 June, 1978 was 307.1 mm, 31% of potential (999 mm).

Figure 7 shows the cumulative actual evaporation calculated from the water balance using the mean soil moisture storage changes from the eight cultivated sites in the Nion subcatchment, plus cumulative catchment mean rainfall. The drainage component of the water balance has been omitted, being relatively insignificant. It can be seen that the evaporation rate increased steadily as the crops developed after sowing, and reached a peak of 2.5 mm/day in January, before the February rainfall. During the February rainy period the evaporation rate fell but increased again after the rain, although not to the same level as in January. After the crops were harvested the rate dropped very markedly to as little as 0.4 mm/day, or 5% of potential, at some sites. At other sites the rate remained as high as 2.3 mm/day; these higher rates were probably the result of lateral abstraction of moisture from the soil in the fields by shrubs and trees along the field boundaries and are not representative of the fallow sites as a whole.

The evaporation rate did not appear to be affected by the amount of depletion that had occurred and did not increase markedly after the February rainfall; this may indicate that moisture availability did not limit evapotranspiration. If this is so, the annual evaporation will be fairly constant in most years, and the soil moisture depletion will depend largely on the amount and timing of winter rainfall events.

Data from the depletion periods following the 1977 and 1978 monsoons have been combined to produce Figure 8. Points worth noting are the very small drainage component and the fact that the trends of actual and potential evaporation are completely out of phase, their rates coinciding only briefly, at the end of the monsoon and in January.

### III THE INFLUENCE OF SOIL CONDUCTIVITY ON RECHARGE

The main objectives of Phase II of the study were to investigate the processes of soil moisture and groundwater recharge and to derive semi-quantitative estimates of recharge.

#### Experimental methods

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 conductivity data together with the potential gradients measured under the natural soil moisture regime. In the dry season the zero flux plane method was used to estimate drainage and evaporation (see appendix).

The method used for obtaining the unsaturated hydraulic conductivity,  $K$ , 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.

$$v = -K(\psi_m, \theta) \frac{d\psi}{dz}$$

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.

#### Selection of sites and observational procedures

Three sites were selected for Phase II, one representing the deep soils and two representing the shallow soils. Their locations are shown in Figure 1. The deep soil site was at Dhaturi in Area III. 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. During the course of the study it became evident that data from the Nipanian site would be inadmissible because the roots of nearby perennial vegetation appeared to be abstracting water laterally from beneath the experimental plot. Results from this site are therefore not discussed.

At each of the sites, two replicate sets of instruments were installed on adjacent plots about 6 m 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. Both sites were equipped with storage raingauges (generally read daily) and tipping bucket gauges with solid state loggers.

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 in Area I and because (as was discovered later)

this site was on the boundary between Areas I and II/III, and included a thin layer of unstructured clay/silt between the structured soil and the weathered basalt.

Once the soil had 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 and were sealed in. A large tent was erected over the plot to prevent rainwater collecting on the plastic sheet and to reduce thermal effects on the tensiometers. Observations of soil moisture were made at approximately two day intervals initially but later the drainage rate became very slow and 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 Dhaturi (where there was a resident observer) the tensiometers were read twice daily, at 06.00 hrs and 18.00 hrs.

At the Nabibag covered plot observations were started on 25 July 1978 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 and was then covered and operated until March 1980.

The 'natural regime' plots (open plots) were cultivated and weeded in conformity with agricultural practice in the surrounding areas. Wheat was sown on all of the open plots. Observations were made at the same time intervals as at the hydraulic conductivity plots but were continued subsequently.

#### Discussion of the results of Phase II.

The conductivity characteristics derived for both sites are given in Figure 9a and 9b, showing the conductivity as a function of matric potential (tension).

#### The conductivity characteristics

The main features of these conductivity characteristics 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 water head.
- 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; this suggests the presence of unstructured clay/silt which should (in theory) not be present in Soil Area I. However this site is near the border between Area I and Area II.
- 3 At both sites conductivity decreases very quickly with falling matric potential (increasing tension). For example, at Nabibag the saturated conductivity of 0.9 m is 26 mm/day, drops to 1.0 mm/day at a matric potential of - 70 cm H<sub>2</sub>O and to 0.1 mm/day at a matric potential of - 100 cm H<sub>2</sub>O.
- 4 The Dhaturi curves (Figure 9a) show a sharp change of gradient below a conductivity of about 1.0 mm/day. This could represent the transition between the conductivity of the residual fissure system and that of the conductivity of the clay matrix itself.

Plots of conductivity against water content (not shown) demonstrated that very small changes in water content accompany very large changes in 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, because at the initial stage of drainage moisture changes in the upper part of the profile tended to be rapid and could not be measured sufficiently frequently. However, the modest extrapolation shown in the diagrams gives saturated values which are considered to be reasonably accurate but possibly err on the low side. The lower conductivities were also 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. Change within individual layers of the profile was therefore extremely small.

The potential gradients within the profiles also became very small, often less than 0.05 cm H<sub>2</sub>O/cm depth, making them difficult to determine accurately.

#### The hydrological importance of the shrinkage cracks

The Phase II studies demonstrated that the "shrink-swell" process has two important hydrological effects.

- 1 The shrinkage cracks facilitate the early re-wetting of the soil.

The wide open crack system presented to the early rains of the monsoon allow water to enter freely into the soil down to the base of the fissure system. This allows the soil to rewet quickly and rainfall goes preferentially into soil moisture storage before much surface runoff occurs to the rivers. 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<sub>2</sub>O does a clear picture emerge (Figure 10).

As 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 between about 0.6m and 1.5 m, with unsaturated conditions remaining above and below. This is shown by the profiles of 29.7.79 (Figure 10a and 10b) where they cross to the left of the dashed gravity potential line. The saturated zone then gradually expands upwards and downwards to saturate the complete profile. This is also illustrated in Figure 12 which shows the development and decay of the saturated zone, interpreted from the Dhatari plot 1 tensiometer data.

In 1979 the wetting process at the Nabibag site proceeded in exactly the same way, with a saturated zone forming in the profile between 1.0 and 1.6 m (6.8.79) which expanded both upwards and downwards. However, the fusion with the lower water table did not occur at Nabibag in 1979 as there was insufficient rain, but it did occur in 1978, a more normal year.

- 2 The shrink-swell process imparts a permanent structure to the upper 1.5 - 2.0 m of the soil which enhances its conductivity.

The conductivity curves show that conductivity decreases with depth in the upper 1.5 - 2.0 m of the soil profile. The shrinkage cracking observed in the dry season also followed this pattern, being greatest at the surface and becoming invisible (in cropped soils) below about 1.5 m. It seems reasonable therefore to draw the conclusion that the shrink-swell process greatly enhances the conductivity of the soil by creating a soil structure which is not entirely destroyed by re-swelling. This provides the distinction between the black cotton soil and the unstructured, very poorly conductive yellow clay beneath. In places where permanent grass scrub is established this enhancement of conductivity probably extends down to 4 m or more, as does the shrinkage, but this was not proved.

The rapid decrease in the conductivity in the range of matric potential between 0 and - 100 cm H<sub>2</sub>O is evidence that the principal conductive pathways for water movement in the soil are large pores which are full of water only at potentials above - 100 cm. The rapid decrease of conductivity in this range of matric potential is associated with the moisture content reduction of about 0.02 and this indicates that these large pores (diameter 0.03 - 0.3 mm) 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 0.03 mm - - 0.3 mm cracks and fissures remaining between the soil peds after rewetting. Once the macrostructures have emptied, i.e. at matric potentials below about - 100 cm H<sub>2</sub>O, the conductivity has decreased to between 0.1 and 1.0 mm/day and falls steadily with further decreasing matric potential. At these potentials appreciable water fluxes could only occur where potential gradients are very steep, a situation which was never observed to occur during monsoon conditions.

The decrease in the size of the structures with depth is also illustrated by the decreasing air entry values shown by the water release characteristic curves of both sites (Figure 13).

The grass/scrub areas may be important in the recharge process in those parts of Areas II and III where the weathered basalt is within 4 - 5 m of the soil surface. Shrinkage structures here could provide a connection between the upper (black cotton soil) aquifer and the weathered basalt aquifer, as in Area I. Grass/scrub occupies about 10% of the land use and is evenly distributed in small irregular plots and strips along field boundaries and gully banks.

### Drainage from the saturated soil profile

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 Figures 10 and 11. The potential gradient within the saturated zone initially is downward (profiles of 3 and 4 August) indicating continuing drainage, but after this, as the zone expands, the gradient decreases and becomes close to zero when the whole profile is saturated. The decreasing gradient can be seen in Figure 10a but this is particularly clearly shown in Figure 10b 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 Figure 11 also.

Although the initial wetting up process at Nabibag was not observed in 1978, the potential profiles from this site also showed that when the entire profile was saturated, potential gradients in the upper profile were very small, as at 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. At Nabibag (1978) not only were zero gradients achieved but for a few days they reversed and became slightly upward, suggesting that the weathered basalt aquifer was filled and being confined by the soil above. Once this state is achieved all of the rainfall (less evaporation) must be lost as surface runoff and interflow. Figure 14 shows the downward flux for the 0.9 m depth Dhaturi calculated 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 formula 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 Figure 9a) 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 (see appendix).

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 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 in Figure 14 (29/7 - 22/8) is 39.5 mm but the flux for the first 3 days of the event (indicated by the dotted lines) was calculated for the 0.7 m depth because the data for the 0.9 m depth were not reliable during these 3 days. In this period 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, but the estimate is not accurate enough to be certain about this.

The similarity between the calculated flux and the deficit in the measured profile indicates that 7 mm/day probably represents about the lowest probable 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 could be more than 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. Such a surplus would be improbably large considering the very low specific yield of the yellow clay, and a saturated conductivity of 7 mm/day seems more probable therefore.

However, irrespective of the value of the conductivity adopted, the potential gradients show clearly the processes involved. Once the entire profile is saturated the potential gradient tends to zero (e.g. profile of 12.8.79, Figure 11a) and thereafter there can be no significant flux to deep recharge. There is therefore no significant recharge to deeper zones during the monsoon season in spite of the fact that the conductivity is then at its maximum.

The November rainfall event contrasts with the situation during the monsoon period in that the antecedent deficit below 0.9 m then was 11 mm and the calculated flux into that zone was 24 mm, leaving an apparent surplus of 13 mm. On this occasion, a surplus input to levels below 0.9 m would not be expected since there could not have been a deficit below the measured profile as, before the event, the water table had only fallen to 2.5 m. A possible explanation would be that between August and November the conductivity was reduced below the adopted 7.0 mm/day figure (derived for August data) by slow, long term delayed swelling of the clay further closing the macropores. Adoption of a conductivity of 3 mm/day would reduce the calculated flux for the November event to 10.5 mm and thus almost exactly satisfy the antecedent deficit. Evidence supporting the hypothesis of delayed 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 and bulk density changes in the clay did occur.

#### Dry season drainage

Soon after the rains come to an end the combined effect of evaporation and slow residual drainage or interflow creates a "zero flux plane" in the soil profile. Here the potential gradient is zero, marking the position of a plane which divides the upper zone (where the flux is upwards to evaporation) from the lower, draining zone (see Figure 11). The zero flux plane position moves down as the season progresses (Figure 12). The position of the zero flux plane is determined from the

potential profiles (measured by tensiometers) and knowing this, the moisture changes above and below (measured by neutron probe) can be divided between evaporation and drainage. This is explained more fully in the appendix.

At Dhaturi the profile ceased to be saturated to the surface on 12 August 1979 and the profile drained rapidly until 23 August, by which time an identifiable ZFP had appeared. Subsequently for the period from 23 August until 27 November, the drainage at 2.5 m measured by this method was less than 0.01 mm/day. After the November rainfall event the same rate was resumed for the rest of the dry season. Thus, the normal dry season drainage calculated by this method is less than 3 mm.

It is worth comparing the 1979/80 dry season drainage at Dhaturi, calculated by the ZFP method, with data calculated by base flow analysis for the Nion sub-catchment for the 1978/79 dry season.

Period	Mean daily drainage rate	Total
2 Sept 78 - 24 Oct 78	0.34 mm/day	17.5 mm
24 Oct 78 - 28 Feb 79	0.07	8.0
March 1979	0.05	1.5
April 1979	0.03	1.0
May 1979	<0.03	0
		28.0 mm

The 28 mm of drainage from the Nion subcatchment is clearly much larger than the 3 mm estimate for the Dhaturi site. However, 8 mm or so of the Nion drainage should be discounted as this represents saturated drainage arising from the water table falling through the measured profile, which is not included in the Dhaturi figure. Furthermore, the Nion figures reflect the behaviour of the entire sub-catchment and probably include other sources of baseflow such as aquifer drainage. Thus, although it is not possible to separate the dry season soil drainage component from the Nion baseflow, it is clearly much less than 20 mm. The two estimates of dry season soil drainage are therefore not incompatible, and show that it is less than 20 mm, and probably only 3 mm or so; this is a very small proportion of the dry season soil moisture depletion.

By either method it is clear that dry season drainage from the soil profile is very small indeed. It therefore follows that simple measurements of soil moisture depletion can be used to determine crop water use in the dry season, and this confirms the validity of the Phase I estimates of evaporation. It seems reasonable to expect that this approach could be applied more widely in the black cotton soil areas of India.

#### IV CONCLUSIONS

The black cotton soil consists of the upper, structured part of the soil profile. In Area I, principally on the western edge of the Betwa catchment it is less than

2 m thick and overlies directly the weathered basalt. Over the largest part of the basalt area (Areas II and III) the black cotton soil grades down at about 2 m into the unstructured 'yellow clay' (buff silty clay). This latter material may be up to 10 m or more thick, overlying the weathered basalt.

The black cotton soil is extremely uniform in its water holding properties and the depletion of its stored water in the dry season varies around 230 mm, the variation arising from crop type and localised winter rainfall. Depletion is insignificant below 2.5 m in the cropped areas and is mostly restricted to the top 1.5 m. In grass/scrub areas drying penetrates to twice this depth and depletions of around 500 mm are typical.

Actual evaporation reaches a peak of around 2.5 mm/day at the end of January; thereafter it falls gradually until after harvest it falls abruptly to as little as 0.4 mm/day. Actual evaporation is in antiphase with potential evaporation, potential reaching its minimum in January when actual evaporation reaches its maximum.

Drainage from the upper 2.5 m of the soil is only 30 mm (or less) during the dry season, from September to May. Most of this occurs during two weeks immediately after the monsoon. Thereafter, the total drainage for the remainder of the dry season is 10 mm at the most, and probably much less. Exceptional winter rains can occur which completely recharge the soil profile and thus increase this figure (as in November 1979) but these events seem to be very rare.

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 dry season recharge fluxes through the base of the structured soil layer are negligible, and during the monsoon, after the profile beneath has been restored to saturation, any recharge is certainly very much less than 1 mm/day. The cultivated deep soils can therefore be modelled as a tank, with an almost non leaking base, and a capacity of about 230 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), and included at its base a thin layer of yellow clay. However, the evidence concerning soil structuring and its influence on conductivity indicates that where the soils are somewhat shallower, i.e. 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 black cotton soil and the weathered basalt form a composite aquifer. Recharge fluxes are less restricted here because the unstructured layer is absent. The Nabibag data suggest that downward (recharge) fluxes are small once the water table has risen to the surface, indicating 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. The grass/scrub areas may provide recharge in Areas II and III in those places where the weathered basalt is less than 4 - 5 m below ground level. Here the structured soil extends right down to the weathered basalt aquifer and could provide a

pathway for significant inputs, as in Area I, providing that there is capacity within the weathered basalt aquifer.

#### ACKNOWLEDGEMENTS

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We are grateful to ODM for funding the project and for the help and support of the many members of ODM staff who were involved, in particular Mr R Kiernan.

#### DATA

The full set of soil moisture data is retained in the IH databank and a duplicate set is held by the Indian Central Groundwater Board.

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- Bouma, J., 1980. Field measurement of soil hydraulic properties characterising water movement through swelling clay soils. *J. Hydrol.* 45, 149-158.
- Watson, K.K., 1966. An instantaneous profile method for determining the hydraulic conductivity of porous materials. *Wat. Res. Res.*, 2, 709-715.

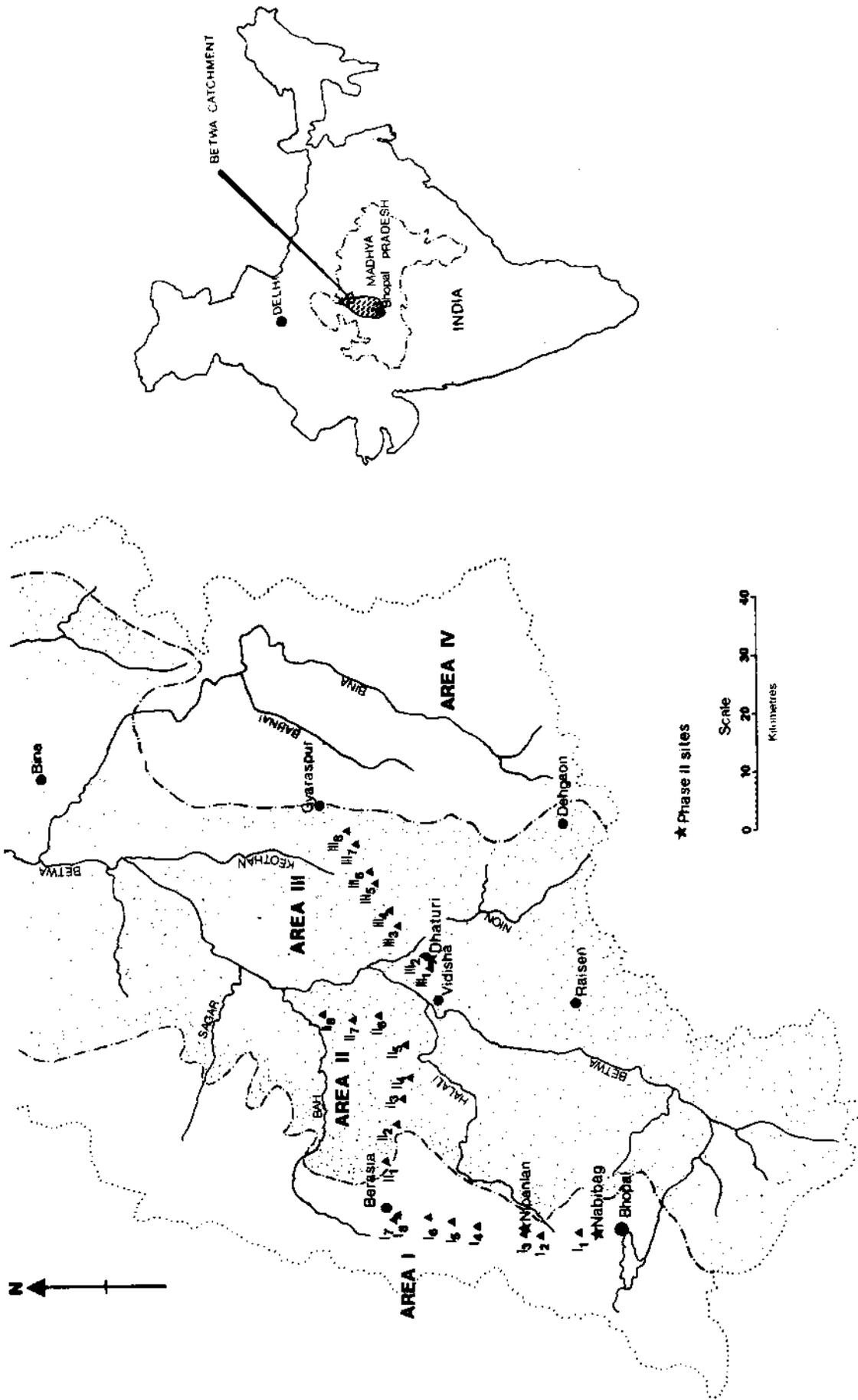


Figure 1. Map showing soil areas, access tube network and experimental sites

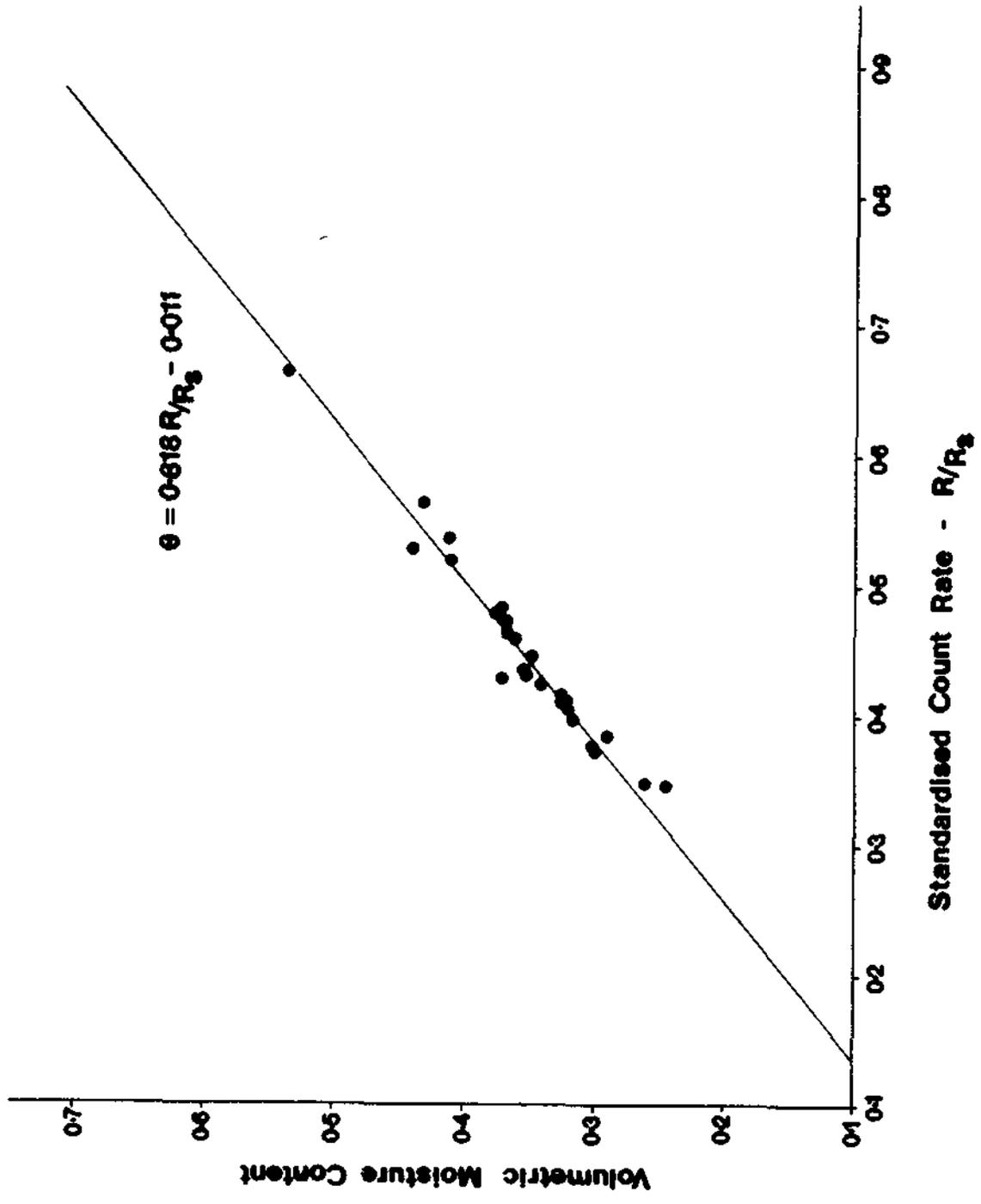


Figure 2. Neutron probe calibration graph for black cotton soils

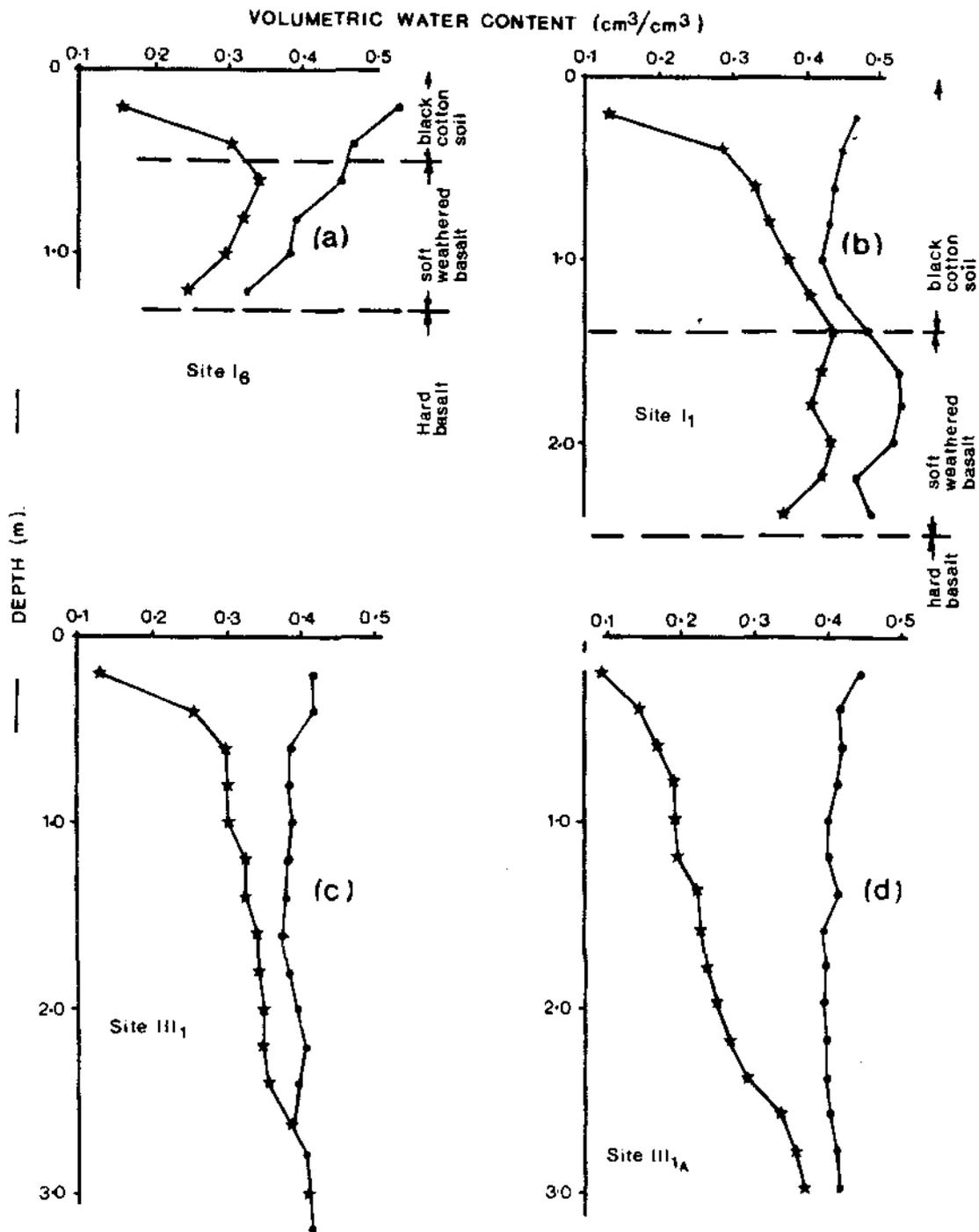


Figure 3.

Wettest and driest recorded profiles

- Area I (a) soil overlying hard basalt directly
- (b) soil overlying weathered basalt at 1.4 m
- Area III (c) a cropped site adjacent to:
- (d) a grass/scrub site.

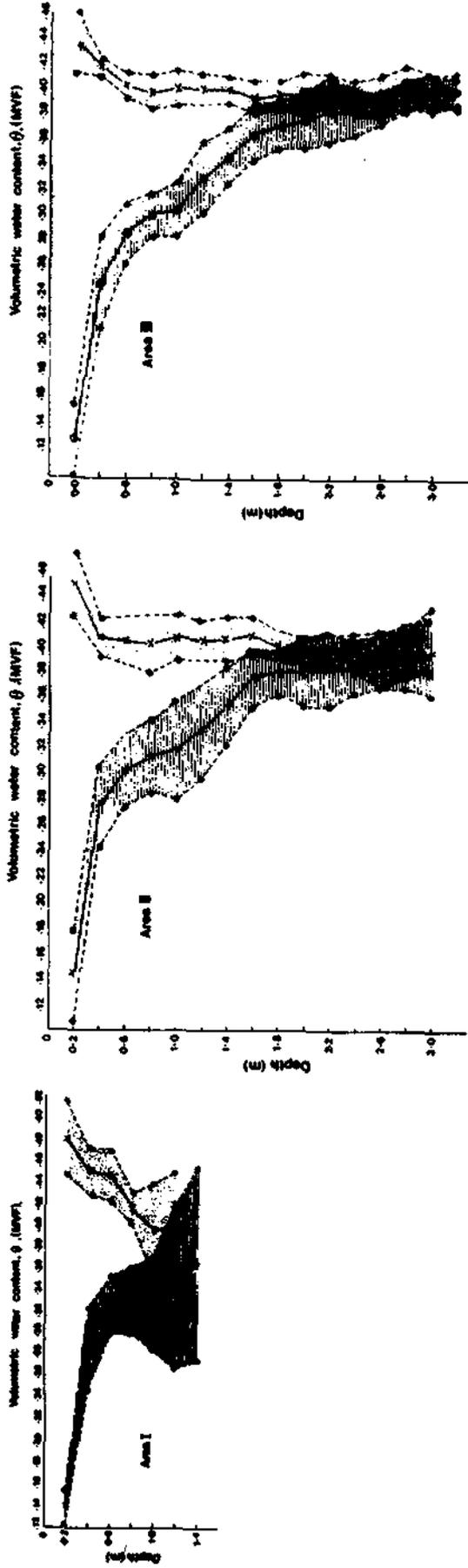


Figure 4. Area mean profiles for wettest and driest state with standard deviation envelopes to illustrate variability within each area.  
 (a) Area I (b) Area II (c) Area III

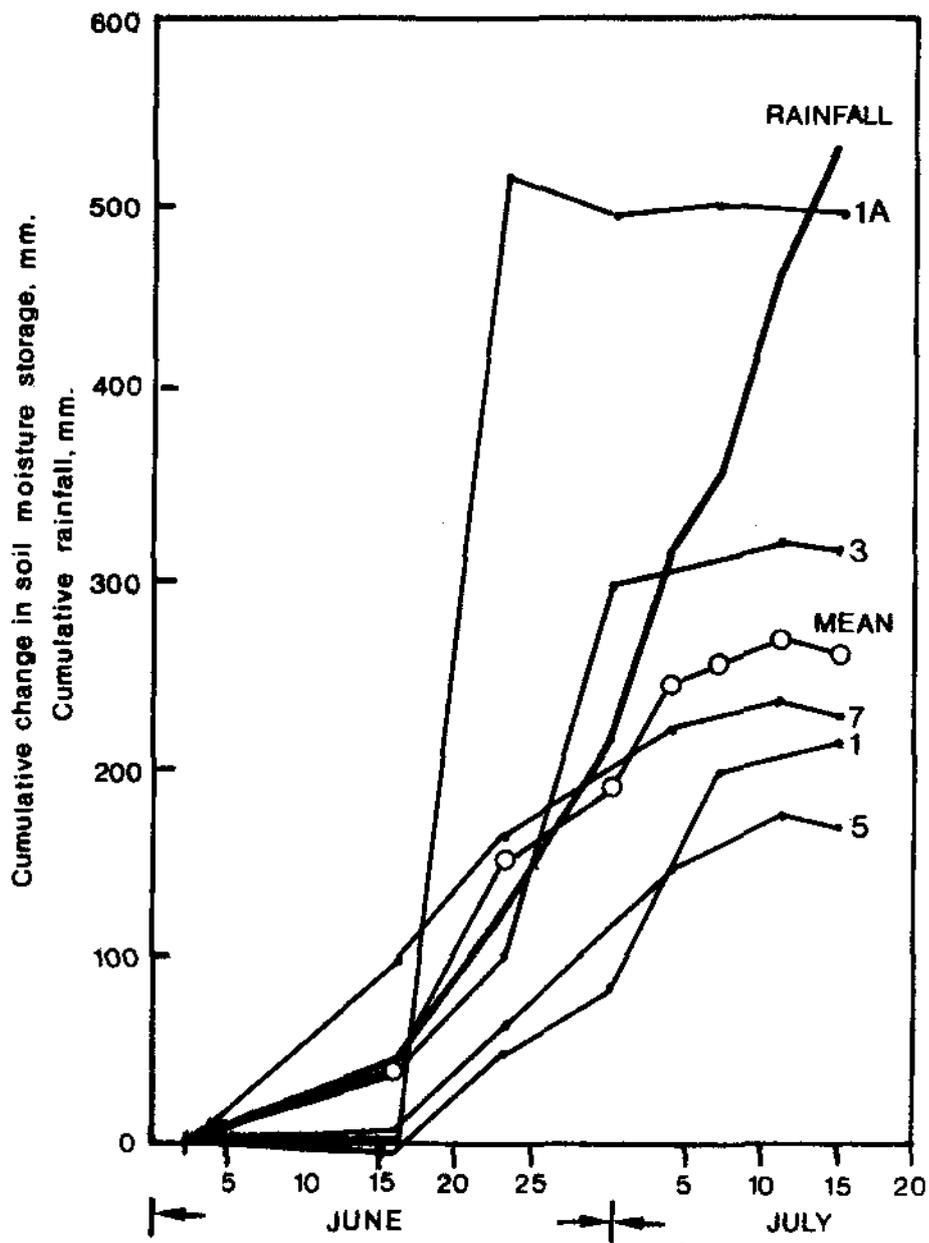


Figure 5. Cumulative rainfall and soil moisture storage, June/July 1978, for five sites in Area III.

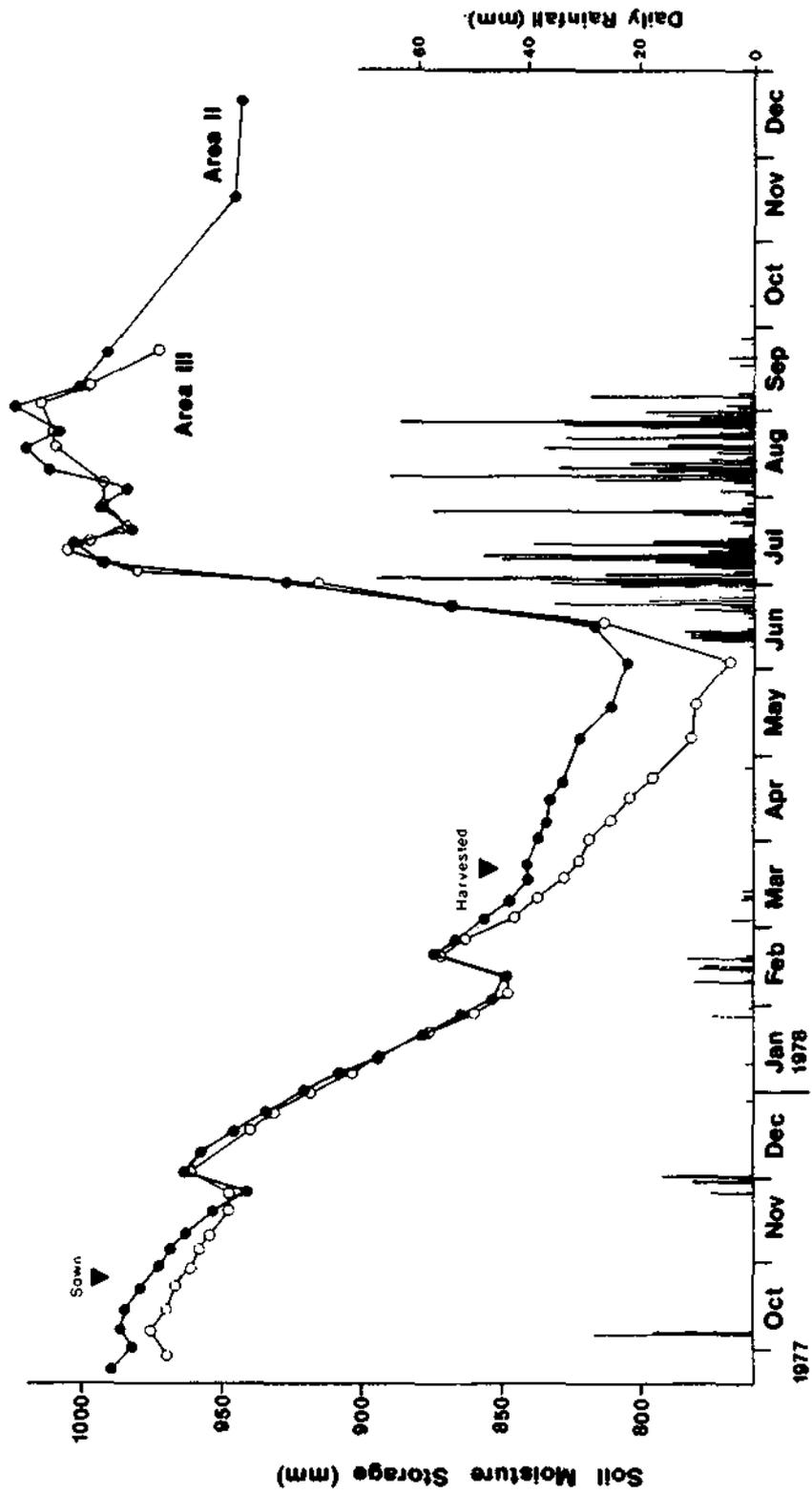


Figure 6. Annual cycle of mean soil water storage to a depth of 2.5 m for Area II and III

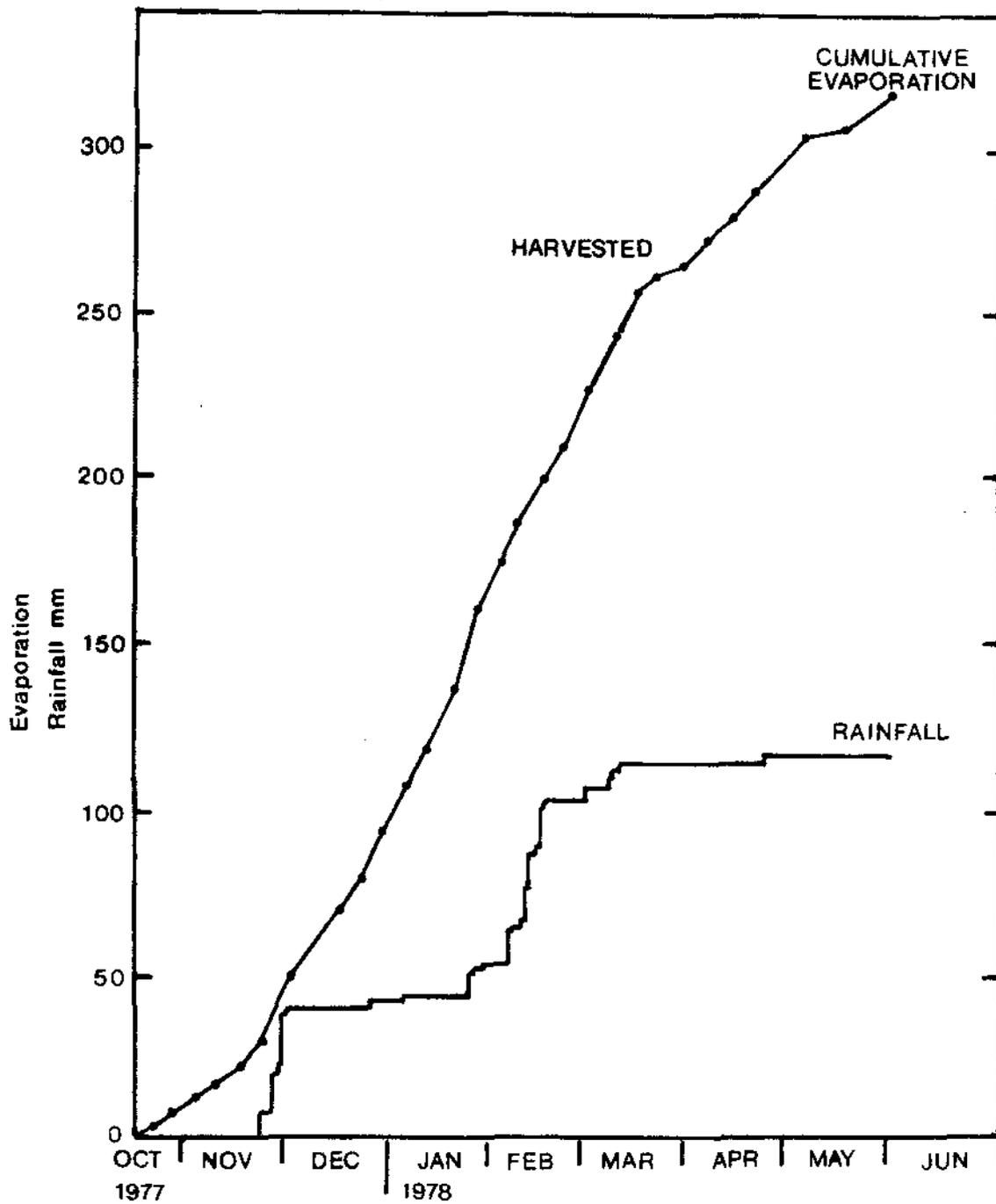


Figure 7. Cumulative measured (actual) evaporation and cumulative rainfall for the Nion subcatchment in the 1977/78 dry season.

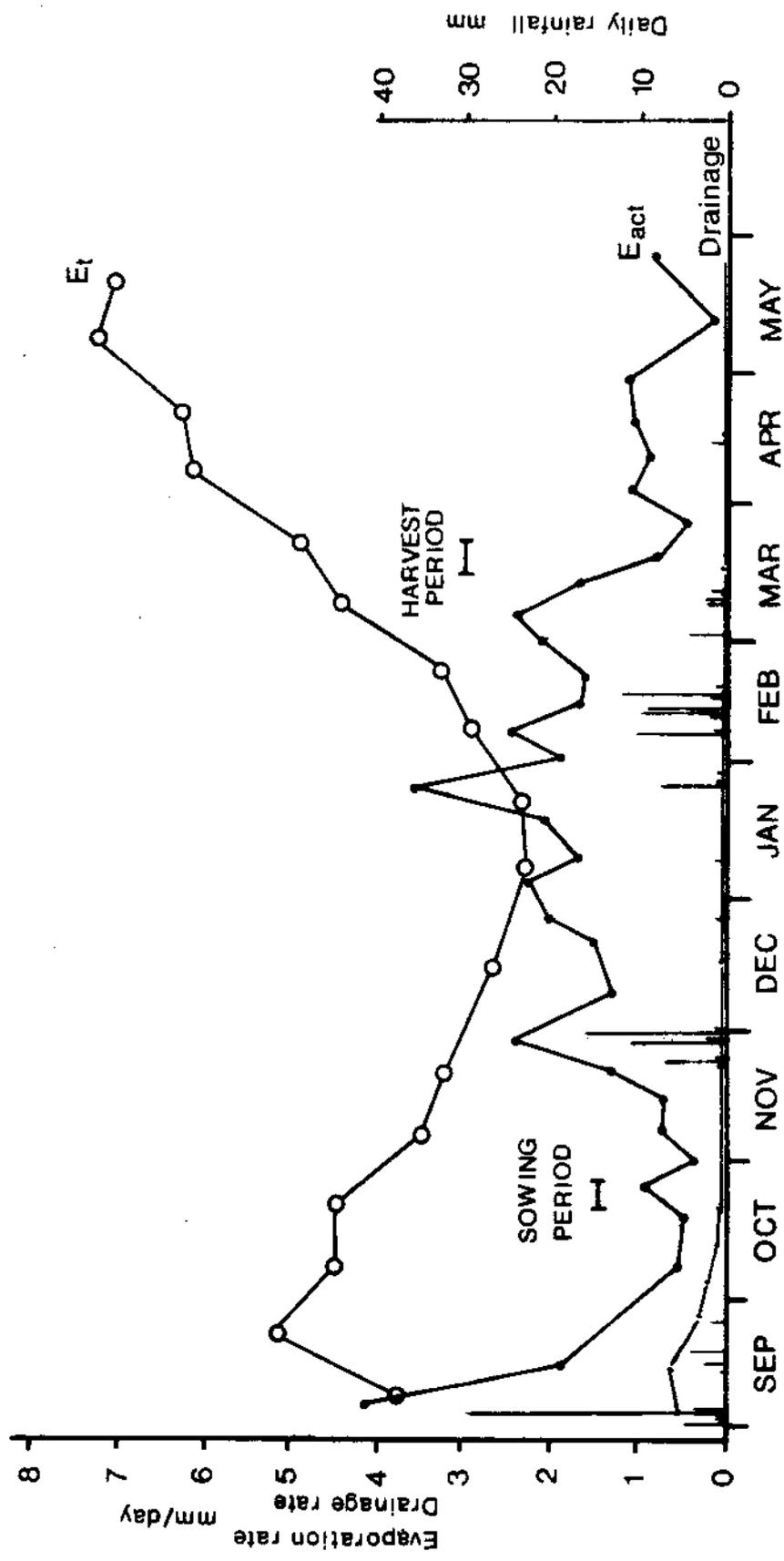


Figure 8. Actual evaporation and drainage derived from measurements of soil moisture depletion, potential evaporation and winter rainfall during the dry season of 1977/78.

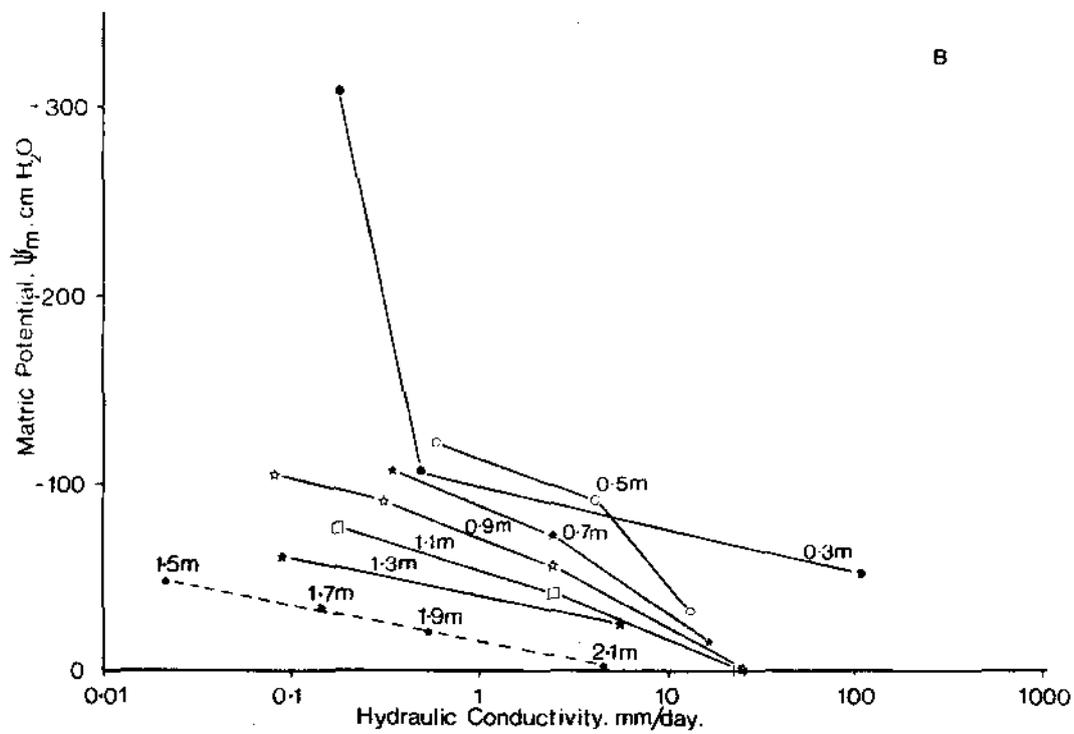
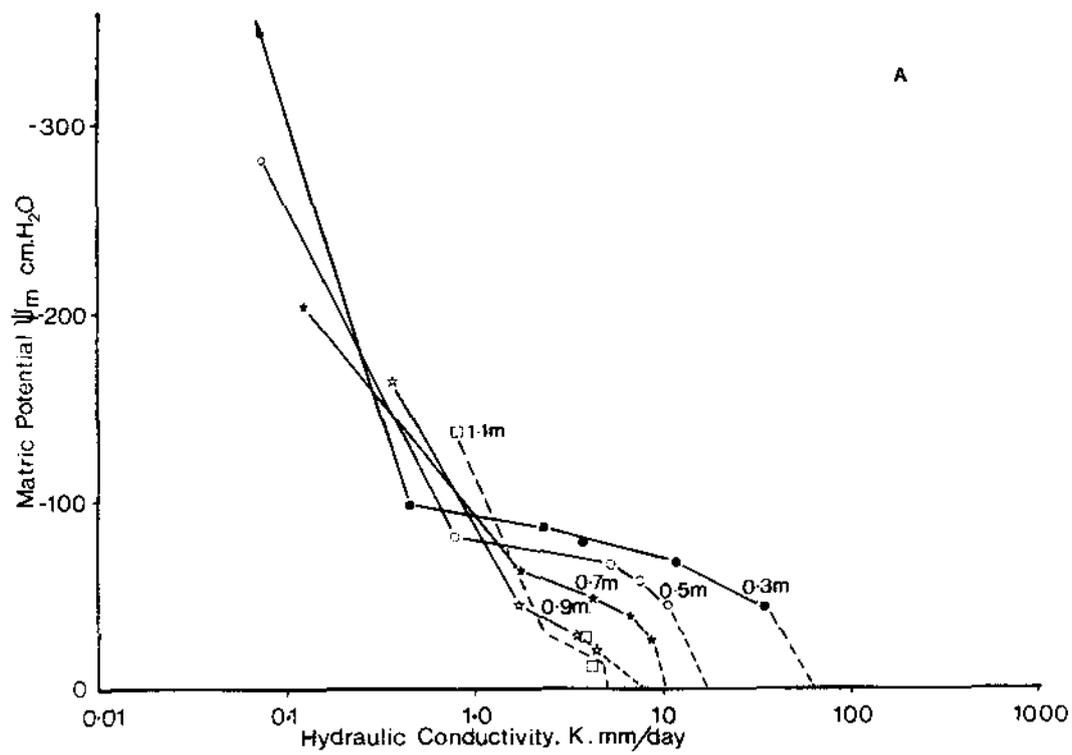
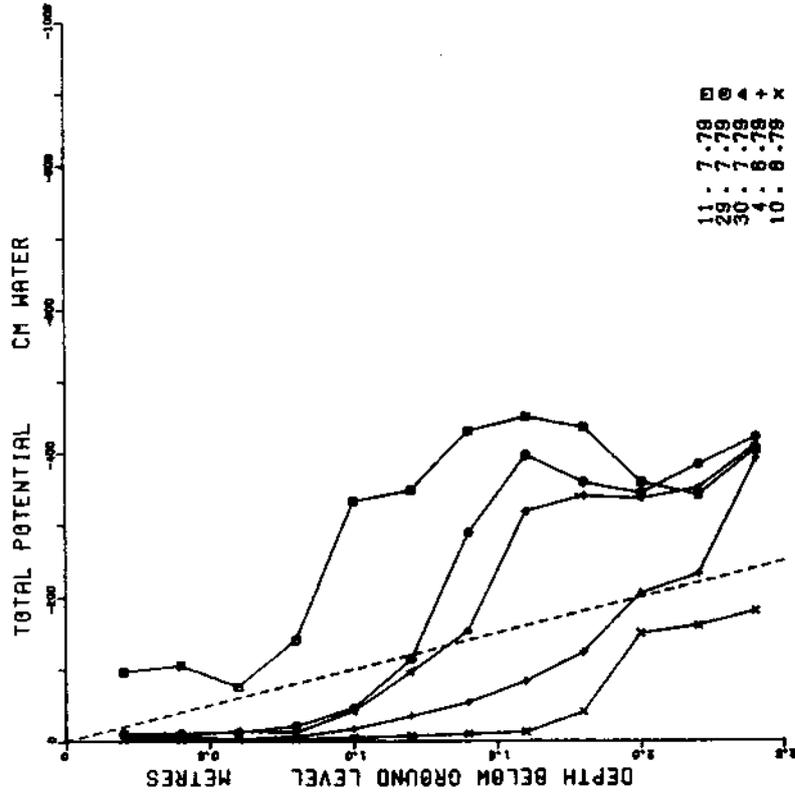


Figure 9. Unsaturated conductivity characteristics  
 (a) Dhaturi  
 (b) Nabibag

AREA: DHATURI 92 PROFILE NO: 43



AREA: DHATURI 92 PROFILE NO: 41

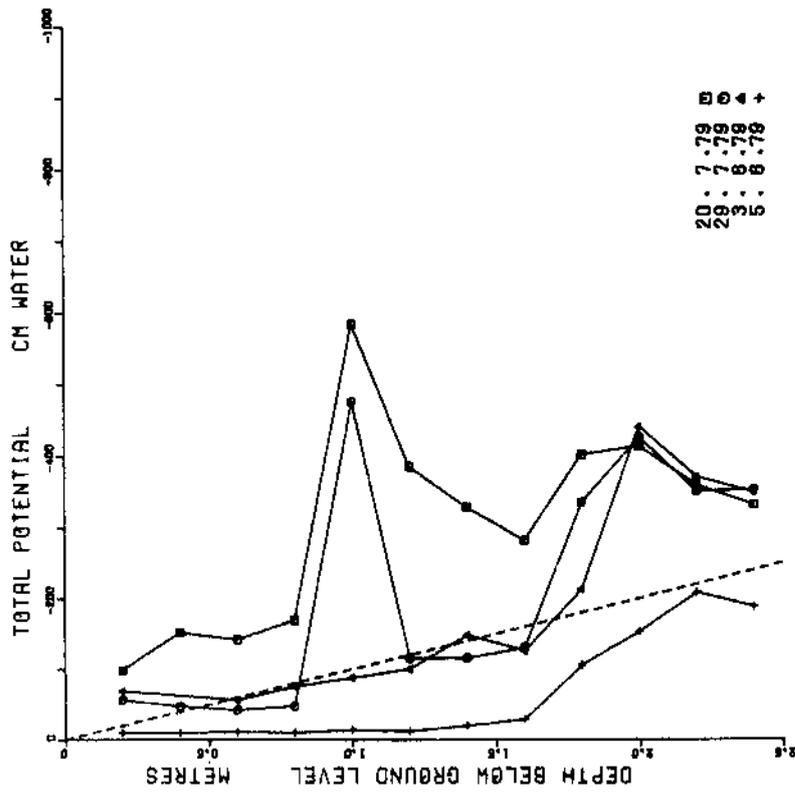
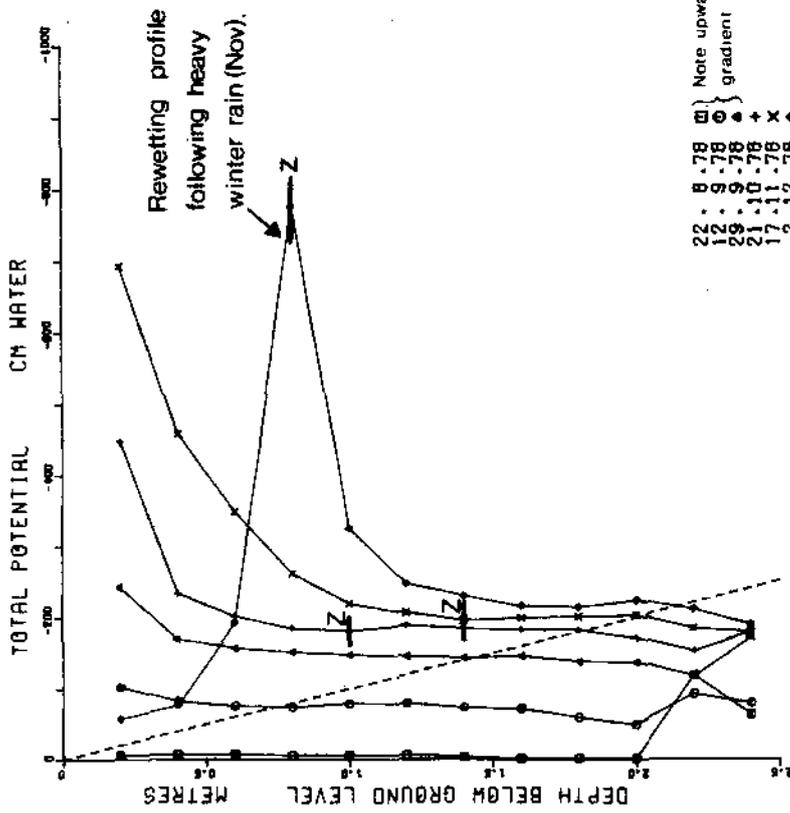


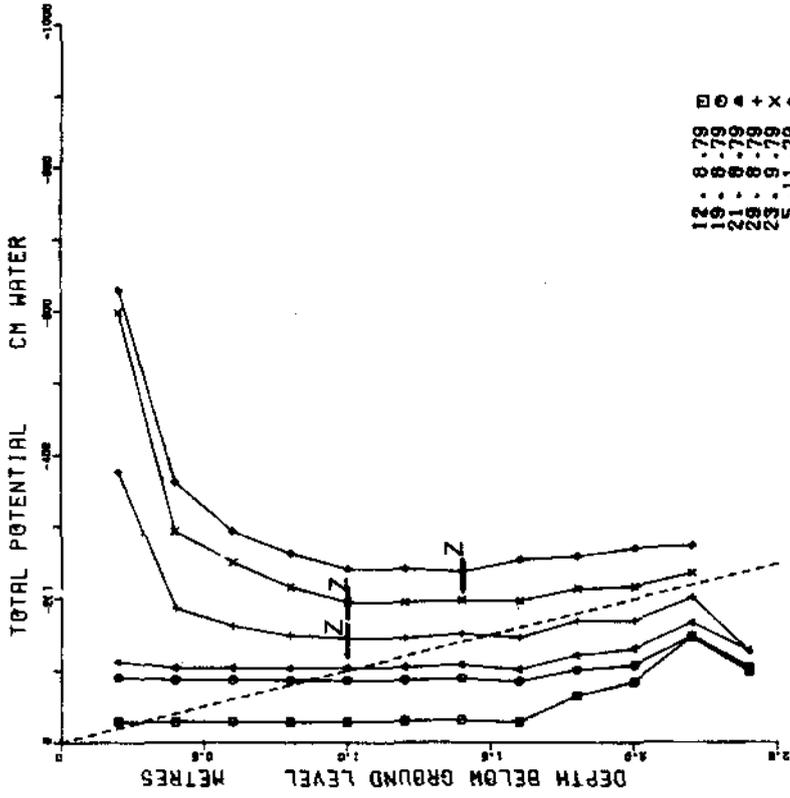
Figure 10. Potential profiles illustrating the wetting process at (a) and (b), adjacent sites at Dhaturi

AREA: NABIBAG 92 PROFILE NO: 01



a.

AREA: DHATURI 92 PROFILE NO: 41



b.

Figure 11. Potential profiles illustrating the early stages of drying, showing the development of the zero flux plane (z), (a) at Nabibag (b) at Dhaturi

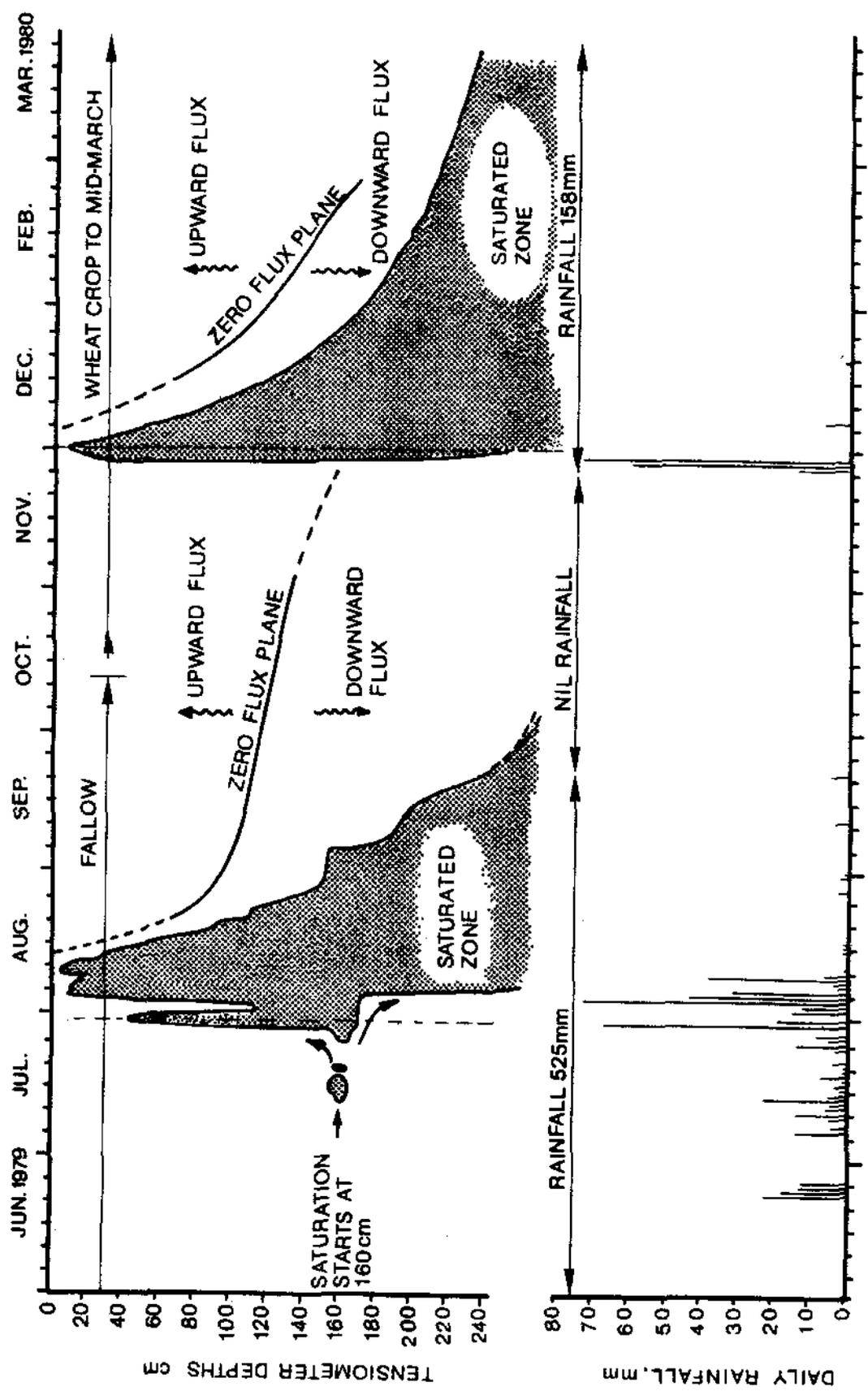


Figure 12. Development and decay of saturated conditions in the soil at Dhaturi, 1979/80.

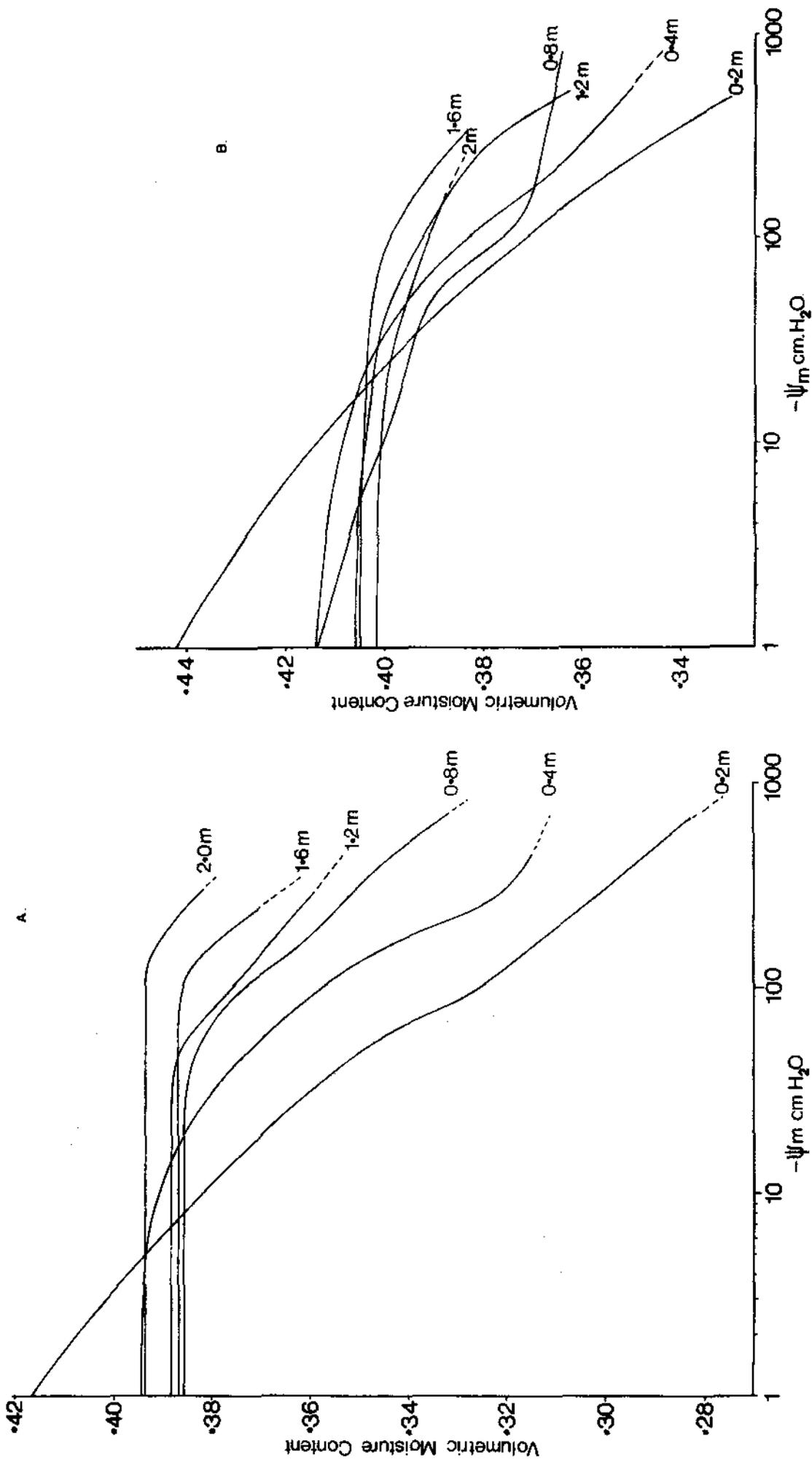


Figure 13. Moisture release characteristics measured in situ:  
 (a) at Dhaturi, (b) at Nabibag

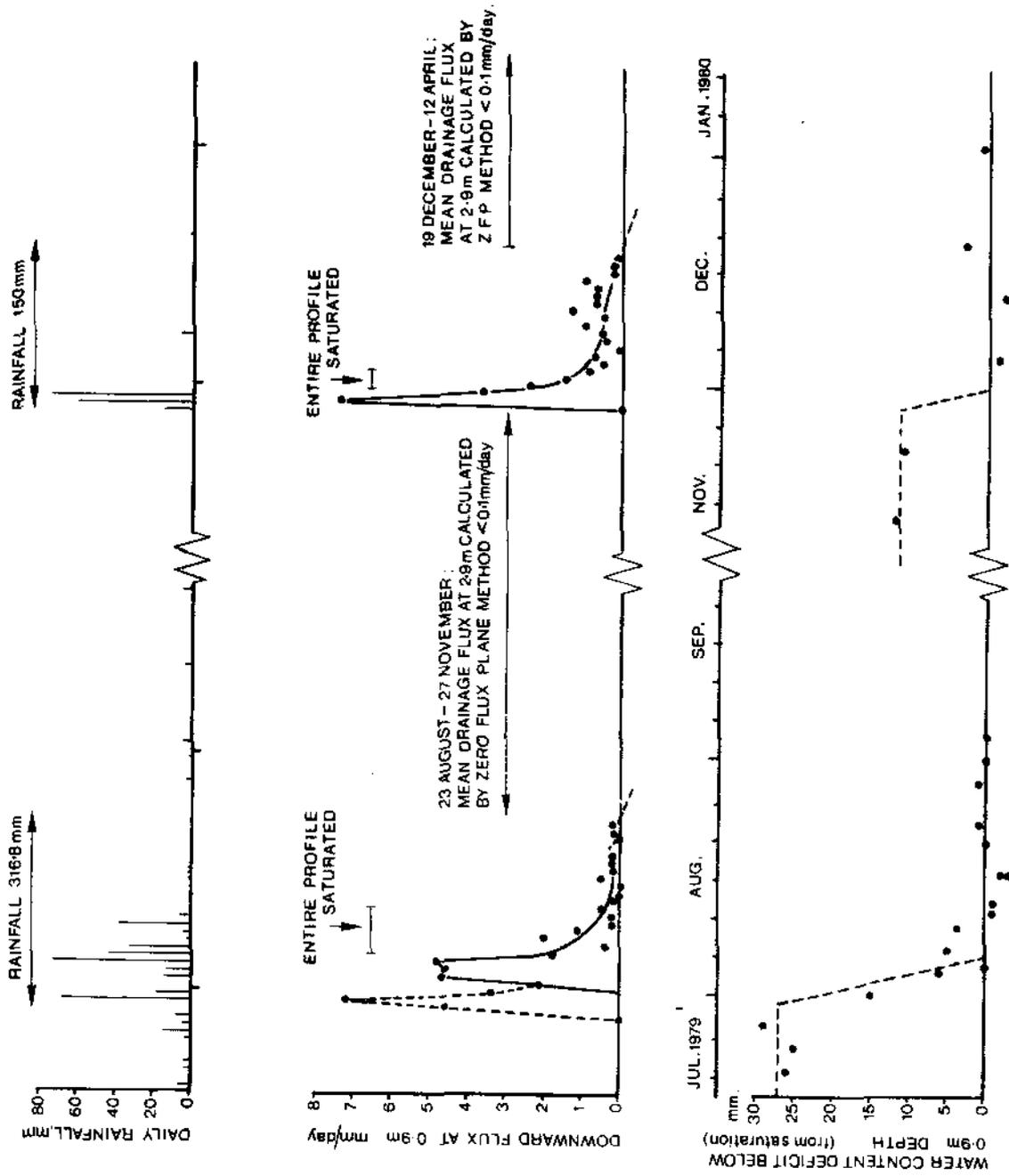
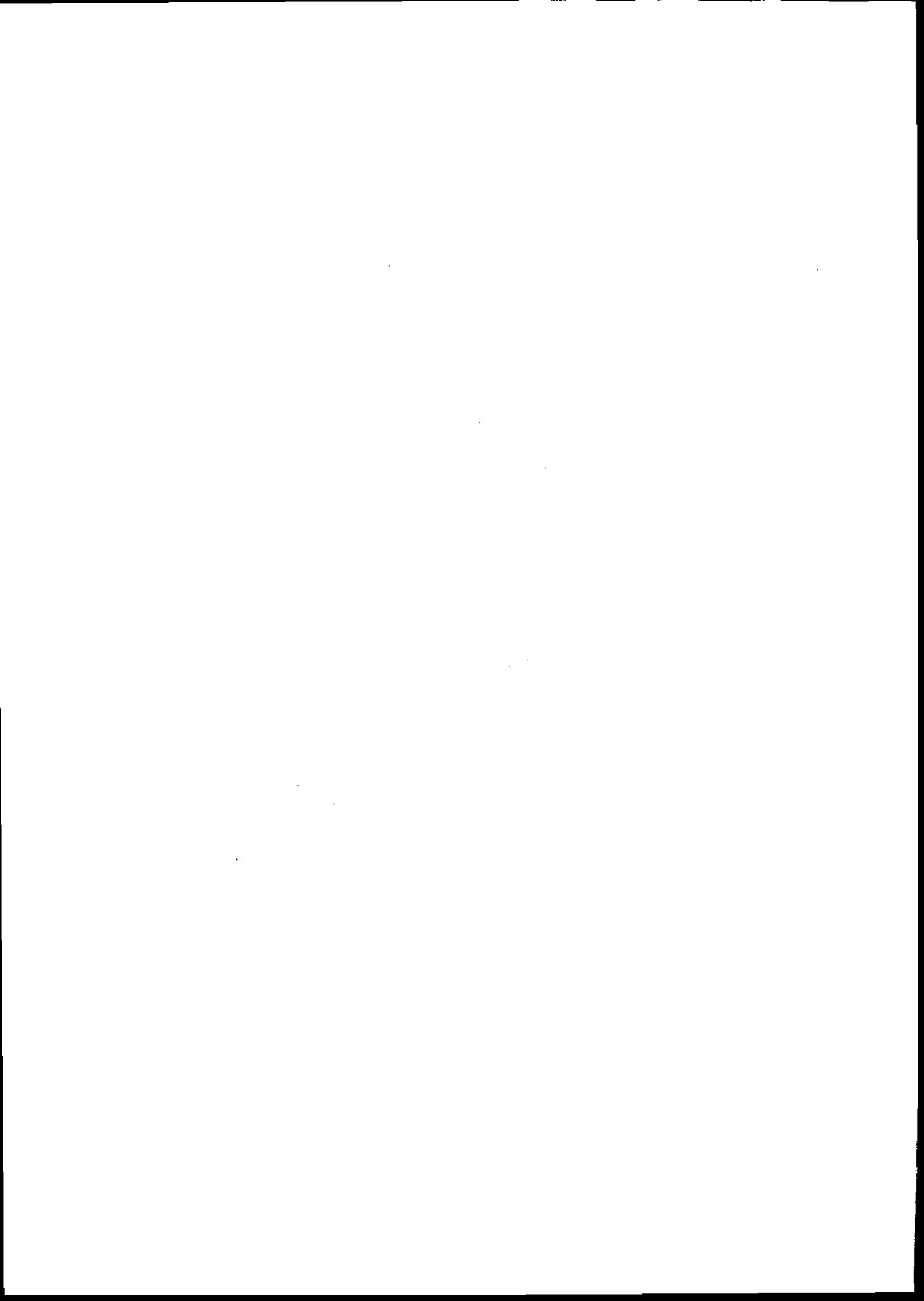


Figure 14. Drainage fluxes at Dhaturi for the 0.9 m depth calculated using a conductivity of 7 mm/day.



## APPENDIX

### SOME BASIC PRINCIPLES OF SOIL PHYSICS INHERENT IN THE BETWA SOIL STUDIES

Water in the soil moves in response to water pressure gradients, expressed in terms of total hydraulic potential  $\Psi$ , representing the potential energy of the water within the soil. The two principal components of total potential are the gravity potential  $\psi_g$  and the matric potential  $\psi_m$ . The gravity potential is that arising from 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 less than this and therefore always negative. The matric potential is due mainly to the surface tension acting on the air-water interfaces in the soil 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, i.e.

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

so that total potential is always negative in unsaturated soil.

Potential is commonly expressed in terms of centimetres of water head (cm H<sub>2</sub>O). Total potentials between 0 and -800 cm H<sub>2</sub>O are generally measured using tensiometers, and lower potentials (higher tensions) can be measured using calibrated gypsum resistance blocks (although with much less accuracy).

Total potential data are presented as 'potential profiles', the total potentials measured within a soil profile being plotted against depth; in these plots gravity potential,  $\psi_g$ , is represented by the dashed line (Figure 1). When expressed in units of centimetres of water head,  $\psi_g$  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 (i.e. where  $\psi_m = 0$ ).

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

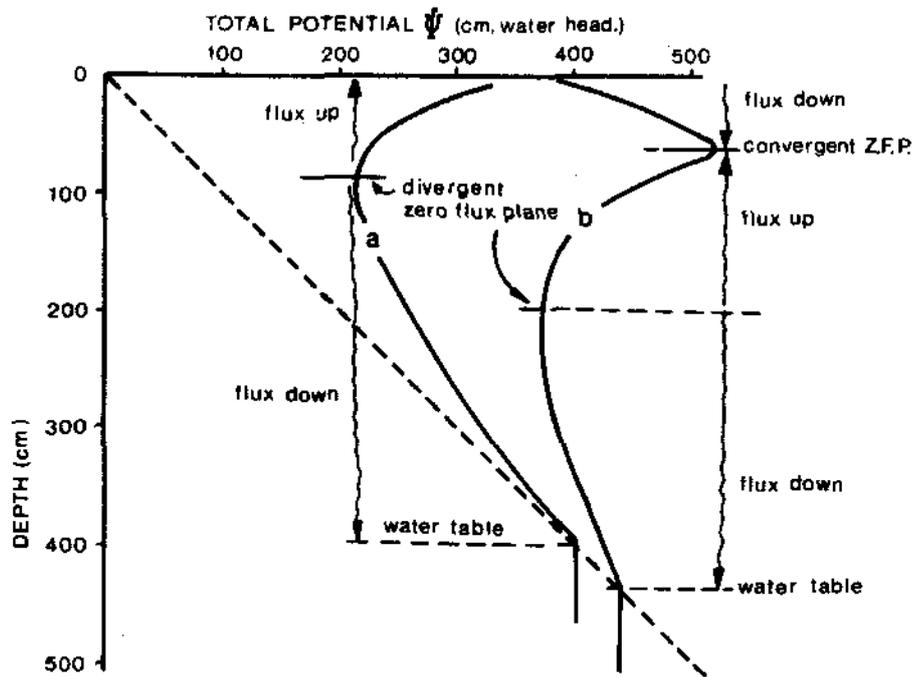
$\frac{d\Psi}{dz}$  is the potential gradient

The hydraulic conductivity ( $K$ ) is a sensitive function of both the volumetric moisture content ( $\theta$ ) and the matric potential of the soil ( $\psi_m$ ). The relationship

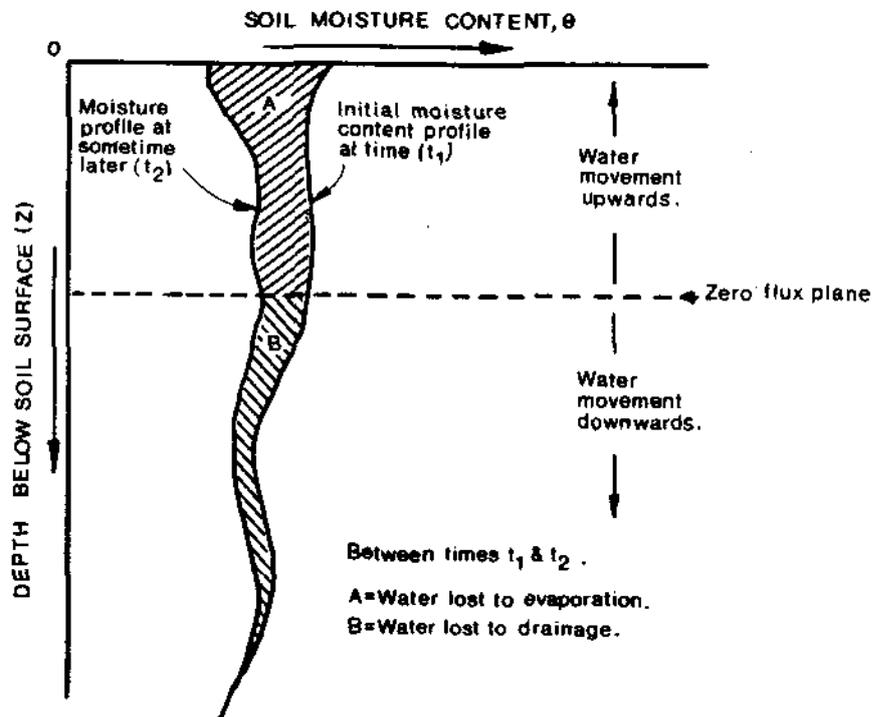
between  $\theta$  and  $\psi_m$  is known as the 'moisture release characteristic' or, if  $\psi_m$  is expressed as  $\log \psi_m$ , as the 'pF curve'.

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, on either side of which the fluxes can either diverge or converge. In the dry season, a divergent ZFP forms, and this separates an upper zone of upward flux (supplying evaporation) from a lower zone in which the flux is downward (drainage). The two potential profiles shown in Figure 1 illustrate this. Profile (a) shows the position of the ZFP at a depth of about 100 cm. The potential gradient above this point is upwards and indicates upward flux, while the potential gradient below it is downwards, indicating downward flux. The ZFP in profile (b) (later in the season) is at a greater depth, and rain entering the upper part of the profile has caused the potentials there to rise and thus created a second, convergent ZFP (equivalent to a wetting front). If there is sufficient rainfall this will move rapidly down the profile until it meets with, and cancels out, the lower divergent ZFP, allowing resumption of drainage throughout the profile.

When a divergent ZFP is present at a known depth within a profile the depletion of moisture storage may be partitioned into upward and downward fluxes, attributable to evaporation and drainage, respectively. This forms the basis of the 'zero flux plane method' for determining evaporation and drainage. Water contents profiles are measured with the neutron probe at intervals of, for example, one week. The difference between the profile water contents on successive occasions, with due allowance for any rainfall which fell in that period, represents the total loss from the profile, the sum of evaporation plus drainage. By knowing the position of the ZFP this loss can be partitioned into the two components, the moisture loss above the ZFP representing the evaporation for the period and that below it representing the drainage; fluxes across any depth can be calculated also. Because the position of the ZFP is normally not static, correction may be necessary to adjust for movement of the ZFP during the period being considered, but for most purposes there is no great loss of accuracy if the ZFP is assumed to move stepwise with time, i.e. to remain constant in depth between each pair of measuring dates.



1. The use of profiles of total soil water potential to identify the position of the zero flux plane (ZFP)
  - (a) early in a dry period, the ZFP moving downwards because evaporation exceeds rainfall.
  - (b) at a later stage: heavy rainfall has created a convergent ZFP at the top of the profile.



2. Calculation of moisture fluxes from a pair of moisture content profiles determined on dates  $t_1$  and  $t_2$ : knowing the position of the ZFP the moisture losses above and below can be assigned to evaporation and drainage respectively.

