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# Soil water storage and groundwater behaviour in a catenary sequence beneath forest in central Amazonia:

## I. Comparisons between plateau, slope and valley floor

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## Abstract

Soil water storage was monitored in three landscape elements in the forest (plateau, slope and valley floor) over a 3 year period to identify differences in sub-surface hydrological response. Under the plateau and slope, the changes of storage were very similar and there was no indication of surface runoff on the slope. The mean maximum seasonal storage change was 156 mm in the 2 m profile but it was clear that, in the dry season, the forest was able to take up water from below 3.6 m. Soil water availability was low. Soil water storage changes in the valley were dominated by the behaviour of a shallow water table which, in normal years, varied between 0.1 m below the surface at the end of the wet season and 0.8 m at the end of the dry season. Soil water storage changes were small because root uptake was largely replenished by groundwater flow towards the stream. The groundwater behaviour is controlled mainly by the deep drainage from beneath the plateau and slope areas. The groundwater gradient beneath the slope indicated that recharge beneath the plateau and slope commences only after the soil water deficits from the previous dry season have been replenished. Following a wet season with little recharge, the water table fell, ceasing to influence the valley soil water storage, and the stream dried up. The plateau and slope, a zone of very high porosity between 0.4 and 1.1 m, underlain by a less conductive layer, is a probable route for interflow during, and for a few hours after, heavy and prolonged rainfall.

## Introduction

This study was part of the Anglo-Brazilian Amazonian Climate Observation Study (ABRACOS) (Gash *et al.*, 1996), the main aim of which was to obtain land surface parameters and calibration data to be used for Amazonian deforestation scenarios in General Circulation Model (GCM) simulations. Three paired (forest and pasture) sites in Western, Central and Eastern Amazonia were instrumented and monitored for 3 to 4 years; data on climate (Bastable *et al.*, 1993, Culf *et al.*, 1996), micro-meteorology (Wright *et al.*,1992, Wright *et al.*,1996), plant physiological responses (McWilliam *et al.*, 1993, Roberts *et al.*, 1996) and soil water content and hydraulic conductivity (Hodnett *et al.*, 1995, 1996, Tomasella and Hodnett, 1996) were collected.

GCMs use a grid with a typical length scale of 200 km. As it is not possible to monitor soil moisture to a depth of several metres on this scale, soil moisture at the central Amazonian site was monitored in three main landscape elements, plateau, slope and valley floor, in which soil water storage changes might differ. It was expected that surface runoff and/or interflow on the slope, and the presence of a water table in the valley, would lead to significantly different soil water behaviour in the three elements. The study area was within a large region with similar soils and geomorphology, on the same geological formation.

This paper compares the soil water storage response in the three landscape elements over a 3 year period to improve understanding of the functioning of the sub-surface hydrological processes in this environment so as to allow better conceptualisation in process-based hydrological models (Dunne, 1983, Klemes, 1983) for Amazonia. Such an understanding may provide a sound basis for the scaling up of processes and suggest ways to incorporate into GCMs the spatial variability of hydrological processes. The results obtained are discussed in the light of the results from the plateau already discussed by

Hodnett *et al.* (1995) and Tomasella and Hodnett (1996). The data presented here provide insights into hydrological processes and the role of the soil in streamflow generation and water table response.

## Methods

### SITE DESCRIPTION

#### *Location and geomorpology*

The study area was located in forest adjacent to a cattle ranch, Fazenda Dimona (2° 19S, 60° 04W) about 100 km north of Manaus. The land surface in the area is a plateau dissected by valleys of various dimensions (Bravard and Righi, 1989). At the study site, the valley, relative to the surrounding plateau, is about 25 m deep and has a wide floodplain with a small stream about 30 m from the foot of the hillslope. The landforms in the study area are similar to those described for the region by Anon (1978). The toposequences are very similar to sections 'A' and 'B' shown by Chauvel *et al.* (1987b) for Bacia Modelo, a 23.5 km$^2$ catchment some 30 km to the south of the study area.

#### *Soils, vegetation and climate*

The soils have formed on largely unconsolidated sediments of the Tertiary Barreiras formation. The plateau soils are clayey oxisols, generally classified as haplic acrorthox under the USDA Soil Taxonomy. They are kaolinitic, with a clay content of 75–85% and a dry bulk density between 0.93 and 1.15 Mg m$^{-3}$. The porosity in the upper 1 m is high (56–64%), but it is mainly concentrated in the macro and meso-pores (which drain rapidly) and in the very fine pores (in which the water is inaccessible to plants) with the result that plant available water is very low. Correa (1985) obtained values of 70 mm m$^{-1}$. Deeper in the profile, the macro and meso-porosity are less and the water availability is lower. These soils are widespread (Anon 1978); almost identical soils have been described by Ranzani (1980), Chauvel (1982) and Correa (1984), for Bacia Modelo.

The soil catenary sequence is similar to that described by Bravard and Righi (1989) for a deeper valley where there was a gradual change in texture from clay on the plateau to sandy clay on the lower slopes. At the study site, there is an abrupt transition to very sandy soils on the valley floor, where there is a shallow water table. The soils are classified as ultic haplorthox on the upper/mid slope and orthoxic paleudults on the lower slope. The sandy valley floor soils are quartzipsamments. The forest is mainly of the terra firme type (Pires, 1978) which occurs on higher ground where there is no seasonal flooding. On the valley floor, where the water table is generally shallow, the forest is characterised by a greater density of palms.

The climate is humid tropical. The mean daily maximum temperature is about 33 °C and there is little seasonal variation. The mean annual rainfall (1966–1992) at Reserva Ducke, about 70 km SSE of the study site, is 2442 mm with a standard deviation (SD) of 306 mm and a range from 1901 mm in 1980 to 3128 mm in 1986. The wettest months are March (304 mm, CV 25%) and April (292 mm, CV 26%) and the driest months are August (95 mm, CV 55%) and September (103 mm, CV 48%). Rainfall intensities can be very high. Out of 162 days of 5 minute rainfall data available from November and December 1992 and May to August 1993 (unfortunately excluding the wettest months), there were 6 events with 5 minute intensities exceeding 100 mm h$^{-1}$ and 4 events with average intensities exceeding 100 mm h$^{-1}$ for 30 minutes. The total rainfall for the 162 days was 1033 mm, of which 47% fell at an intensity exceeding 50 mm h$^{-1}$.

### EXPERIMENTAL DESIGN

#### *Soil water content, potential and water level measurement*

Figure 1 is a schematic cross-section from the plateau to the valley, showing the location of the instruments. Soil water content was measured using an IH neutron probe (Model IH III, Didcot Instrument Co., Abingdon, UK) calibrated as described by Hodnett *et al.* (1995). In September 1990, 5 neutron probe access tubes were installed in each slope unit, to 2 m depth on the plateau and slope and 1 m on the valley floor, where in the late dry season, the water table was 0.3 to 0.5 m below the surface. On the plateau, tubes were installed to 3.6 m in October 1991 (replacing those to 2 m) after the data suggested water uptake from below 2 m; resources did not permit deeper tubes to be installed on the slope. The tubes were read at 0.1 m and 0.2 m, and then at 0.2 m intervals to the bottom of the tube.

Soil water potential was measured using mercury manometer tensiometers installed at depths of 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.5, 1.8 and 2.1 m; one set was on the plateau and another at the foot of the slope (max depth 1.5 m).

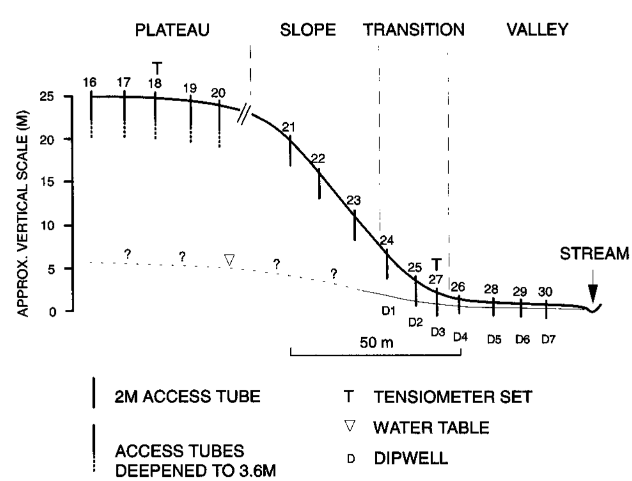


Fig. 1 *Schematic cross-section showing form of hillslope and position of instruments.*

Each set was close to a neutron probe access tube. Water level was measured with a manual dipper in 7 dipwells adjacent to, and paired with, access tubes T24 to T30 and numbered D1 to D7 down the slope. Elevations along the transect and at each measuring point were determined relative to a datum point (ground level at T30) using a surveying level. The maximum slope on the transect was 18%.

*Climatic data*

An automatic weather station operated throughout the study period in an adjacent clearing, about 1 km from the forest instrumentation (Bastable *et al.*, 1993). Rainfall was measured using a tipping bucket gauge, initially logged hourly and subsequently at 5 minute intervals. Unfortunately, the gauge was not very reliable and there are many gaps in the data.

OBSERVATIONS AND DATA PROCESSING

Observations of soil water content, potential and water table level were made weekly from mid-September 1990, except during the periods of intensive micrometeorological studies (September–October 1990 and July–September 1991), when they were made twice each week. The data for the period up to December 1993 are presented here. The readings for the individual tubes were processed as described by Hodnett *et al.* (1996a) to give water contents at each depth and storage (mm) in the 0–1 m, 1–2 m and 0–2 m layers. Mean water contents and layer storage values were calculated for the plateau (tubes T16-20), slope (T21-23) and valley floor (T26 and T28-30). Tubes T24, T25 and T27 were in a transition zone between the slope and the valley floor where the soil water storage was influenced by the valley floor water table in the wet season. Tensiometer manometer measurements were converted to total hydraulic potential (relative to the ground level at each set). The water levels in the dipwells were measured relative to the top of the lining tube and then converted to depth below datum.

# Results

SOIL WATER STORAGE

Figure 2 shows the forest soil water storage to a depth of 1 m for the plateau, slope and valley floor for the period from October 1990 to December 1993. Also shown is the water table depth below the valley floor (D4) and the rainfall between water content measurements. Periods when the raingauge was malfunctioning are indicated by negative values (–5 mm).

*Plateau/slope comparisons*

The soil water storage changes in the 0-1 m layer on the plateau and the slope were virtually identical throughout the entire period, regardless of the season. This is remarkable, and indicates that surface runoff, if any (it was never observed), does not lead to differences in the wetting-up of the profile. The data imply that the processes of water input, redistribution and loss (deep drainage and uptake to supply evapo-transpiration) are almost identical on the plateau and slope.

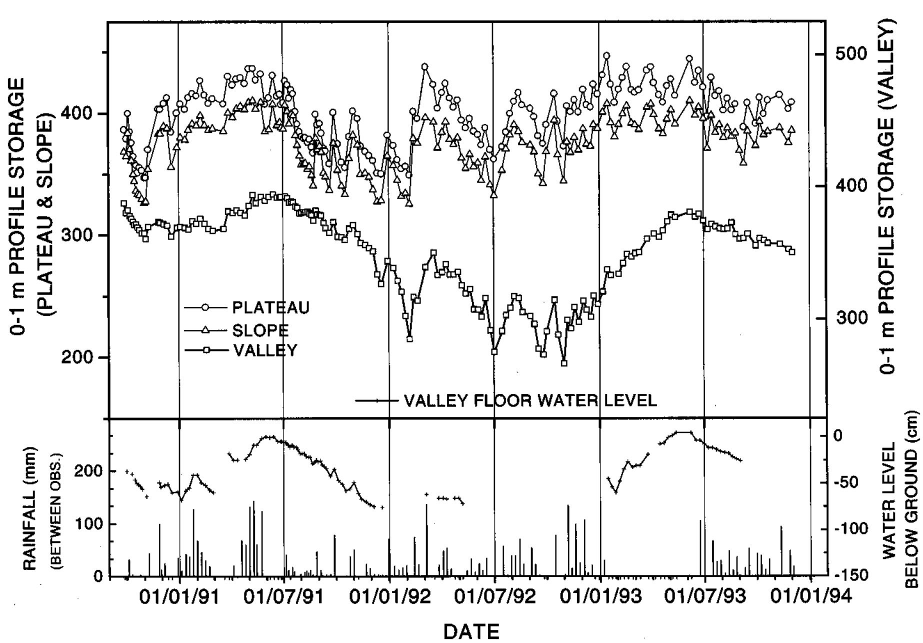


Fig. 2 *Plateau, slope and valley floor. Profile soil water storage (mm) to a depth of 1 m for the period from September 1990 to December 1993. Also shown are the water table depth on the valley floor and the rainfall between soil moisture measurements.*

The storage in the profile was consistently greater on the plateau than on the slope, reflecting the greater clay content of the plateau soils (and hence a greater content of bound water). However, water content changes were similar. The minimum profile storage was observed on 5 November 1990 (plateau and slope). The storage was almost as low on 6 February 1992, which was unusual as January and February are, on average, among the wettest months.

Once the profile has wetted up at this site, the profile storage (as shown by weekly data) does not vary much in the wet season because of frequent rainfall and because drainage is rapid following large rainfall events (Hodnett *et al.*, 1996a). Any storage peaks are short-lived. The storage in the profile remained close to this characteristic wet season level for 7 months in 1990–91, 2 months in 1991–92 and 9 months in 1992–93.

### *Valley floor groundwater levels*

Up to October 1991, the water table was never more than 0.6 m below the surface. It reached a peak in June 1991 after the 1990–91 wet season and was within 0.3 m of the soil surface for almost 5 months. The water level then fell gradually to below a depth of 0.8 m (the maximum depth of the dipwell) in December 1991. During the weak 1991–92 wet season, the water table rose above 0.8 m only in March and April 1992. The water level then fell to a minimum of 1.83 m below the surface on 4 November 1992 (measured in a newly installed dipwell). The water levels recovered between January and May 1993 and the water level recession in 1993 was similar to that of 1991.

### *Valley floor soil water storage*

These soil water storage data (to 1 m depth) comprise soil water AND groundwater for the period when the water table was less than 1 m below the surface. As a result, changes in soil water storage were generally small; up to October 1991, the maximum storage change in the valley was 33 mm, compared to 90 mm on the plateau. Between July and October 1991, the storage decreased steadily, interrupted by very minor increases (typically 15 mm) following rainfall. On the plateau and slope, the same events led to storage increases of up to 70 mm. These data suggest that on the plateau, there was no deep drainage following these events but, in the valley, much of the rainfall must have drained rapidly to the water table and thence to the stream. The valley floor minimum storage was observed in October 1992, almost two years after the minimum on the plateau and slope.

After the water table rose back into the 1 m measured profile in January 1993, the soil water storage showed a steady and almost unbroken increase until June 1993, as the water table continued to rise. During this period, the soil water storage on the plateau and slope remained largely constant, close to the typical wet season level, with maximum changes of about 30 mm in response to rainfall events.

### *Maximum observed storage changes*

Table 1 shows the maximum observed profile storage changes to 1 m and 2 m depth in the three landscape elements. The maximum storage occurred on 10 May 1991 on both plateau and slope. The minimum was observed on 2 or 5 November 1990. In Table 1, the storage changes for all elements have been calculated between 5 November 1990 and 10 May 1991. The valley floor maximum and minimum were observed on 14 June 1991 and 31 October 1992 respectively and the change in storage between these dates is also shown.

For the 2 m profile, the maximum storage changes observed under the plateau and slope were 154 mm and 159 mm. On the slope, the change in the top metre was slightly less than on the plateau but was compensated by larger changes in the second metre. Spatial variability, as indicated by the standard deviations (SD) of the maximum changes, was low on both plateau and slope. Over the period when the maximum storage change was observed on the plateau and slope, the change in the valley was only 33.5 mm (SD 20.4 mm). Tube 28 on the valley floor showed much larger storage changes than the other tubes

*Table 1.* Maximum observed soil water storage changes (mm) for plateau, slope and valley

| | PLATEAU Min. 5/11/90 Max. 10/5/91 | | SLOPE Min. 5/11/90 Max. 10/5/91 | | VALLEY 5/11/90–10/5/91 | | VALLEY Min. 31/10/92 Max 14/6/91 | |
|---|---|---|---|---|---|---|---|---|
| Layer | 0–1 m | 0–2 m | 0–1 m | 0–2 m | 0–1 m | 0–2 m | 0–1 m | 0–2 m |
| Mean | 89.4 | 153.9 | 82.7 | 159.3 | 33.5 | 33.5[1] | 127.9 | — |
| S.D. | 3.0 | 5.7 | 4.7 | 5.0 | 20.4 | 20.4 | 14.1 | |
| Max. | 85.2 | 145.9 | 76.3 | 153.0 | 19.6 | | 117.5 | |
| Min. | 93.3 | 162.4 | 87.3 | 165.2 | 68.7 | | 152.0 | |

[1] Same as 0.1 m, as water table above 1 m bgl between these dates

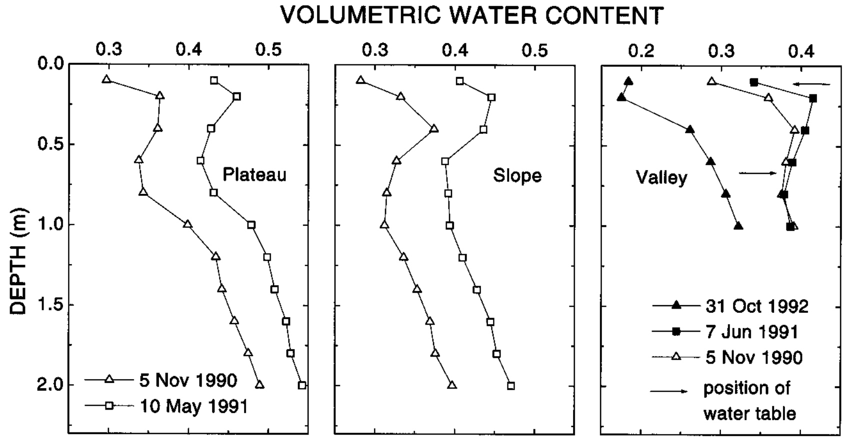


Fig. 3 *Wettest and driest water content profiles for plateau and slope (10 May 1991 and 5 November 1990) and valley (7 June 1991 and 31 October 1992). The profile for 5 November 1990 (when the plateau & slope were driest) is also shown for the valley.*

because it was on a slight mound and had a deeper unsaturated zone. The storage change for the 3 tubes with the shallower water table was 21.8 mm (SD 2.2 mm).

The mean maximum storage change for the 1 m valley profile was 128 mm; this was significantly higher than on the plateau/slope, where the largest change for any tube was 93 mm. At Tube 30, in the centre of the floodplain, the change was 152 mm; changes are larger than on the plateau and slope due to the sandier texture of the soil, and because the wettest condition observed was saturation. Saturated conditions may have occurred on the plateau and slope for brief periods but were observed only once under the weekly monitoring regime.

## DISTRIBUTION OF WATER CONTENT CHANGES WITH DEPTH

Figure 3 shows profiles of mean water content for the dates when the highest and lowest storage was observed in the 3 landscape units. The form of the water content profiles on the plateau and slope was very similar; both showed a zone of low water content between 0.5 and 1.2 m in both the wet and the dry profiles; the importance of this is discussed later. Below 0.3 m on the slope, the largest water content changes in the profile did not exceed 0.11 MVF and were typically about 0.08 MVF. These values are indicative of the available water capacity (AWC) of the soil, but over-estimate it slightly because the wettest profile is above field capacity and part of the change is drainage. The changes on the slope were slightly higher than those on the plateau, but these seasonal water content changes are very low compared to those in other soil types (Hodnett *et al.* 1995). The less clayey slope soils have been shown to have a slightly higher AWC in the upper metre than the more clayey plateau soils (Correa, 1984).

The wettest of the valley profiles in Fig. 3 shows the water table within about 0.1 m of the surface. On 5 November 1990, when the plateau and slope were driest, the water table was at 0.6 m and the very small water content changes from the wettest condition can be seen. The difference between the wettest and driest profiles for the valley shows that changes above 0.6 m were much larger (0.24 MVF at 0.2 m) than on the plateau and slope, but similar below 0.6 m.

## SOIL WATER DEPLETION IN DRY PERIODS

Figures 4a, b and c show, for the plateau, slope and valley floor respectively, the rate of decrease of soil water storage plotted against profile storage for periods with less than 2 mm of rain between soil water measurements. The plateau and slope showed a similar relationship, with the highest depletion rates (4–5 mm day$^{-1}$) when the storage in the top 2 m was high and the lowest (<1 mm day$^{-1}$) when storage was near its minimum. Shuttleworth *et al.* (1984) measured daily forest transpiration rates of up to 4.3 mm day$^{-1}$ and soil water depletion rates in excess of this are likely to include an element of drainage. The pattern for the valley was opposite to that on the plateau and slope. The lowest soil water depletion rates (0.5–1 mm day$^{-1}$) occurred when storage was high (water table near the surface) and the highest (3 mm day$^{-1}$) when storage was low (water table below 1 m).

During the early part of the dry season, groundwater flow from beneath the hillslope towards the stream maintains the water table near to the surface and replenishes the water taken up by the valley floor forest. As the groundwater discharge decreases, the forest has to take up progressively more of its requirement from stored soil water.

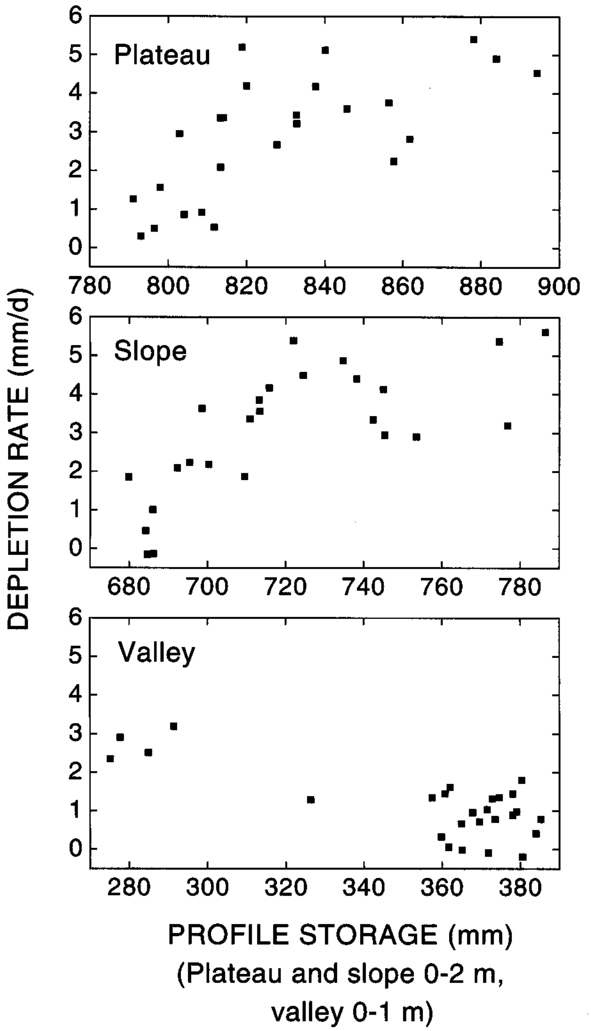


Fig. 4 *Soil water depletion rates (2 m profile) as a function of profile storage, for periods with less than 2 mm of rain: (a) plateau, (b) slope and (c) valley floor (1 m profile).*

## EVAPOTRANSPIRATION RATES DETERMINED FROM THE WATER BALANCE

The driest soil water conditions in the study period developed at the end of the 1990 dry season. After a 32 mm rainfall event on 3 October, there was only 6 mm of rain in the period up to 5 November 1990. Measurements for this period are examined in detail.

### *Plateau and slope*

Figure 5 shows profiles of total hydraulic potential for the plateau after the rainfall on 3 October. On 5 October there was a marked wetting front between 0.8 m and 1.0 m depth. The rest of the profile was at very low potentials (close to the limit of, or beyond the range of tensiometers) showing that, before the rain, the forest had already dried the profile to below 2 m. A zero flux plane (ZFP) developed in the wetted zone and uptake caused potentials at all depths to fall below tensiometer range again after about 10 days. They remained so for a further 3 weeks until heavy rainfall occurred after 6 November. During the period between 3 October and 5 November, storage in the 1–2 m layer decreased by only 6.2 mm and 8.5 mm on the plateau and slope respectively, confirming that both had already been largely dried out.

Figure 6 shows the cumulative rainfall and cumulative loss (evapo-transpiration + drainage) from the plateau and slope 2 m profiles, estimated from the soil water balance for the same period. The drainage loss was negligible because field capacity for these soils is between –6 kPa and –10 kPa (Reichardt, 1988) and matric potentials in the lower profile were < –60 kPa throughout the period.

The cumulative loss curves were virtually identical, and provide a further demonstration of the similarity of the soil water behaviour under plateau and slope. During the period shown, there was a large decrease in uptake rate from the 2 m profile. Between 5 and 16 October, loss rates determined from the water balance were 3.82 mm day$^{-1}$ and 3.62 mm day$^{-1}$ for the plateau and slope respectively. For the 14 day period to 5 November, the mean rates for the plateau and slope were only 0.66 and 0.74 mm day$^{-1}$ respectively. The negligible loss rates over the final 7 days show that uptake from the upper 2 m of the profile had virtually ceased. It is very unlikely that the forest could survive on this very low rate of uptake while showing

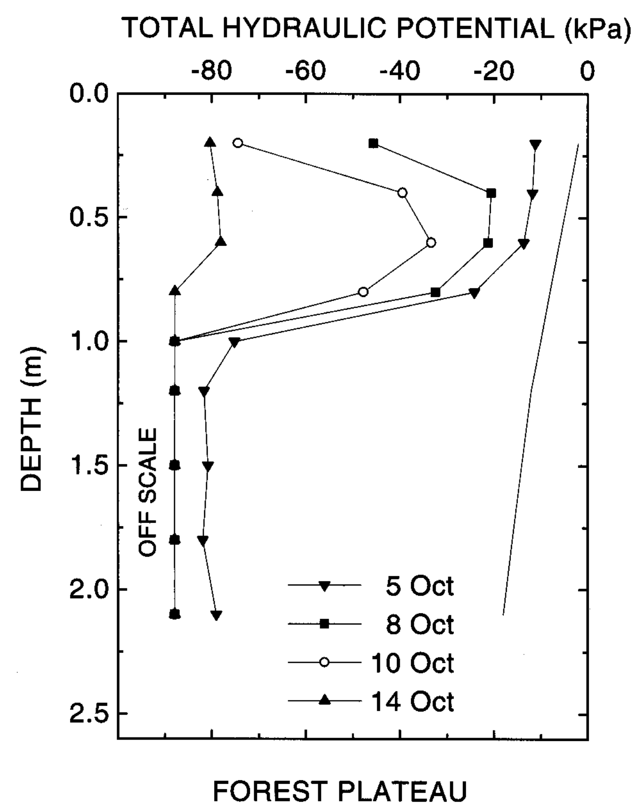


Fig. 5 *Plateau, profiles of total hydraulic potential following the rainfall event of 32 mm on 3 October 1990.*

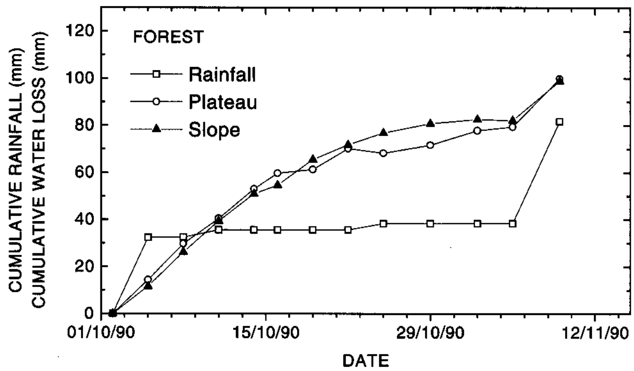


Fig. 6 *Plateau and slope. Cumulative water loss from the 2 m profile during the 1990 dry season, determined from the water balance.*

little sign of stress, and it was almost certainly taking water from greater depth. If uptake rates of 3.6 mm day$^{-1}$ were sustained, about 75 mm of water would have been taken up from below 2 m in the period up to 5 November. Data from the 3.6 m plateau tubes installed in October 1991 showed that uptake can occur from below this depth (Hodnett *et al.*, 1995, 1996b). Deep uptake has also been noted by Nepstad *et al.* (1994), although in an area with a more pronounced dry season.

*Valley and lower slope, groundwater contribution to transpiration*

Figure 7 shows, for each of the slope and valley tubes, the mean rate of soil water depletion for the period 5 October

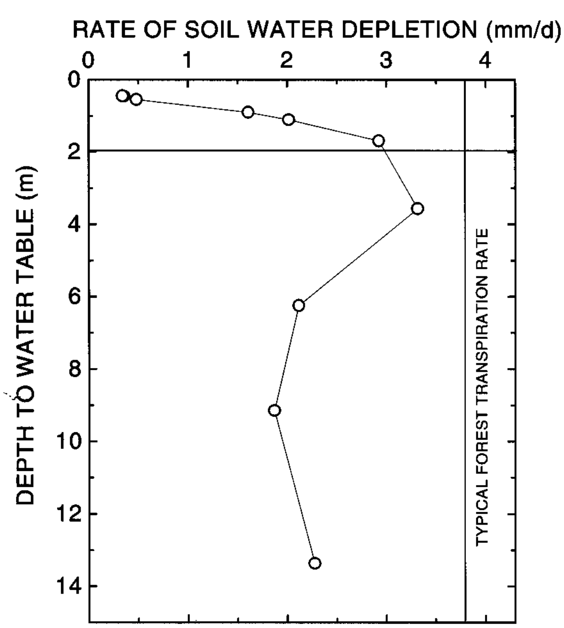


Fig. 7 *Soil water depletion rate at the individual slope and valley tubes plotted as a function of depth to water table for the period 5 October–5 November 1990.*

to 5 November 1990 plotted against the mean depth to the water table. For Tubes 24–30, the water table depth was determined from the dipwell data. For Tubes 21–23, higher on the slope, the depth to the water table was estimated from their elevation and by extrapolation of the groundwater gradient measured between the dipwells furthest up the slope (D1 and D2). A mean dry season evapotranspiration rate of 3.8 mm day$^{-1}$, taken from Shuttleworth (1988), is shown for comparison. The depletion rates calculated for the tubes where the water table was within 2 m of the surface account for all of the possible unsaturated zone water content change, but where the water table was deeper, the depletion rates do not account for uptake from the unsaturated zone between 2 m and the water table.

The data show a decreasing contribution from the water table (and/or the deep unsaturated zone) as the water table depth increases to a depth of 3.6 m. If the forest evapotranspiration rate is estimated to be 3.8 mm day$^{-1}$, the data suggest that 91% of this was contributed from the water table at 0.45 m, compared to 47% from 1.11 m and only 13% from 3.6 m. However, between a water table depth of 3.6 m and 6.3 m, there appears to be a transition to a larger contribution from the profile below 2 m (mean 45%) for the upper slope tubes. For the plateau tubes, the mean estimated contribution from below 2 m was similar (50%).

Soil water potential profiles for the same period are shown for the valley in Figure 8. This tensiometer set was about 0.6 m above the valley floor where, at the start of the study, the water table was at about 1 m depth. One day before the 32 mm event on 3 October, there was an upward gradient from the water table at a depth of 1.04 m; a day after, potentials throughout the profile had increased and the water table had risen to 0.96 m, but uptake from the surface layers had already re-established an upward potential gradient above 0.4 m (Fig. 8a). Profiles from 4 October onward are shown in Fig. 8b. Over the next 18 days, the potentials became increasingly negative in the layers above 0.7 m (below tensiometer range at 0.2 and 0.4 m). At 0.8 m and below, the potential decreased in equilibrium with the water table, which fell 0.22 m over this period.

## WET SEASON PROCESSES

*Plateau*

Figure 9 shows water content profiles for 6 February (driest), 5 March and 19 March for two of the five 3.6 m tubes on the plateau to illustrate the progress of the wetting front after the extended dry spell up to February 1992. The behaviour at the other three tubes was very similar. On 5 March, there was a well defined wetting front between 1.8 and 2.0 m, with no evidence of wetting below this depth. This suggests that, at this forest site, the advance of the wetting front is remarkably uniform and progressive. The wetting front had reached 3.6 m by 19

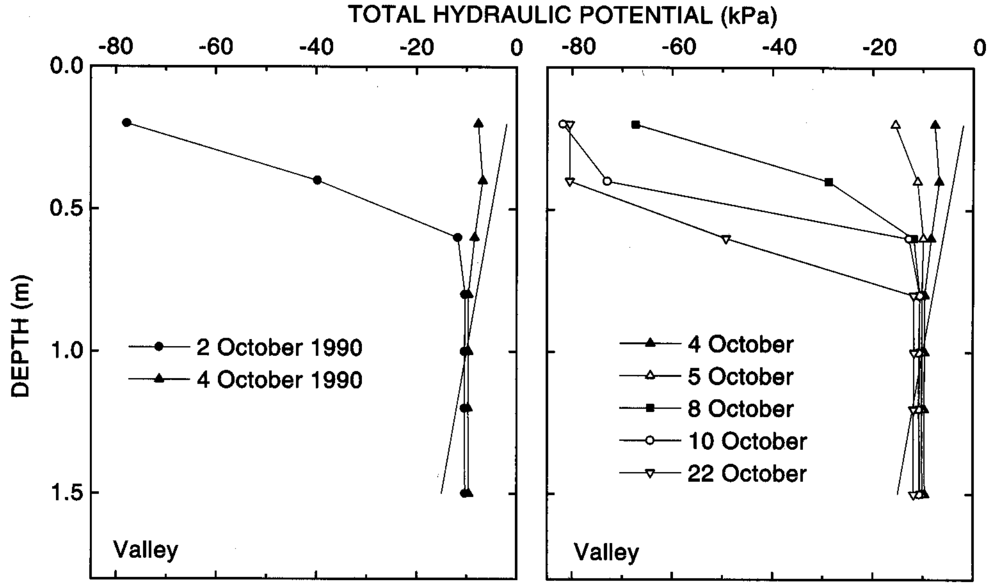


Fig. 8 *Valley, profiles of total hydraulic potential (a) one day before and one day after the 32 mm rainfall event on 3 October 1990, and (b) over the subsequent 18 day dry period.*

March. The very small seasonal water content change (0.02–0.03 MVF) in the profile below 3 m is apparent.

Figure 10 shows wet season profiles of total soil water potential for the forest plateau site during March 1991. A typical wet season profile, on 17 March, shows unsaturated conditions with a downward potential gradient throughout the profile. Uptake of water from the upper profile was rapid and by 19 March there was a steep upward gradient, with a ZFP at 0.4 m depth. On 28 March, one day after 146 mm of rain, saturated conditions were observed on the plateau (below 1.2 m) for the only time during the study period, under the weekly monitoring regime. It is likely that the saturated zone would have extended higher in the profile closer to the event.

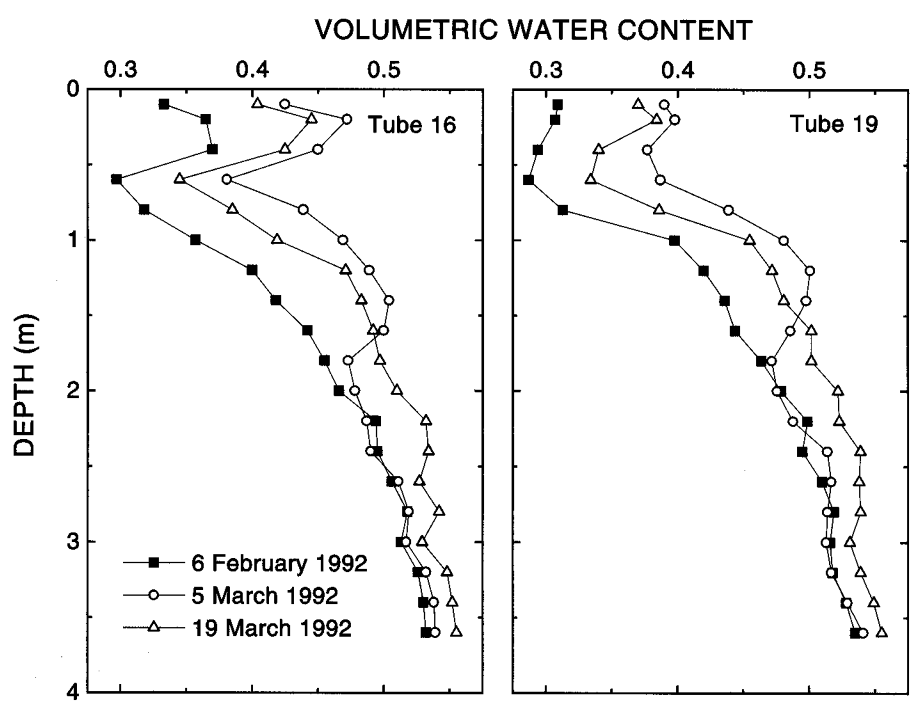


Fig. 9 *Plateau water content profiles showing the wetting up of the 3.6 m profile between 6 February 1992 and 19 March 1992, with a clearly defined wetting front at about 2 m on 5 March. Examples are shown from (a) Tube 16 and (b) Tube 19.*

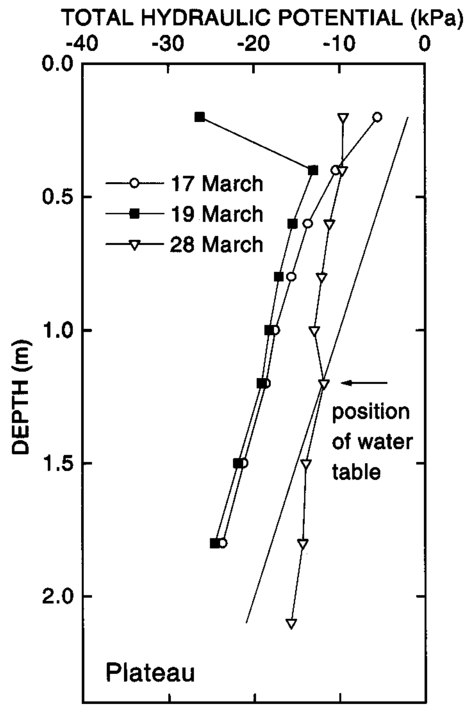


Fig. 10 *Plateau, profiles of total hydraulic potential during the 1991 wet season. The profile for 28 March shows saturation below 1.2 m, the only time that this was observed on the plateau.*

*Valley*

Figure 11 shows profiles of total hydraulic potential at the end of the 1990-91 and 1991-92 wet seasons. On 24 and 31 May 1991 the water table was at 0.65 m, with a steep upward gradient from the water table on 31 May. In contrast, on 30 April 1992, there was a downward gradient to a water table at 1.4 m; by 14 May, the upper layers had dried to beyond tensiometer range and the water table had fallen to 1.55 m. The final profile, for 31 October 1992 (the driest conditions observed) when the water table was at 2.3 m, shows an upward gradient from 1.5 m, which was particularly steep above 1.2 m. Except for periods of one or two days after rain, there was almost always a gradient from the water table towards the surface at this site; a ZFP was rarely observed. The gradient in the zone immediately above the water table (the capillary fringe) was generally small because the unsaturated hydraulic conductivity is the same as at saturation. The sharp change in gradient marks where the conductivity decreases abruptly at the top of the capillary fringe.

FLOODPLAIN AND LOWER SLOPE WATER TABLE BEHAVIOUR

Figure 12 shows water level data from dipwells D1, furthest up the slope, to D4, on the floodplain at the foot of the slope, and the water table gradient between D1 and D3 (see Fig. 1) for the entire study period. In the first part of the 1990–91 wet season, water levels increased sharply following rainfall events, and recessed between events. After March 1991, water levels rose almost continuously to reach a maximum on 7 June, almost a month after the maximum storage was observed in the 2 m profile on the plateau and slope. Increases in water level ranged from 0.79 m at D1, furthest upslope, to only 0.35 m at D7 on the floodplain. After June 1991 water levels decreased almost continuously to below the base of the dipwells in December 1991. The stream, whose bed is about 0.8 m below the datum level, became dry at about this time and did not flow again until early 1993. Water levels rose only briefly in 1992 but recovered in the 1992–93 wet season, reaching the dipwells in January and then rising continuously until May.

The weekly data always showed a water table gradient from the slope towards the valley floor. During the early part of the 1990–91 wet season there was an overall decrease in the the water table gradient. After March 1991 the gradient increased to a maximum in June 1991 and then decreased during the following dry season. A similar pattern was observed in 1993, indicating an increase of flow toward the valley beginning a few months after the start of the wet season, and a gradual decrease in flow during the dry season *and* early wet season.

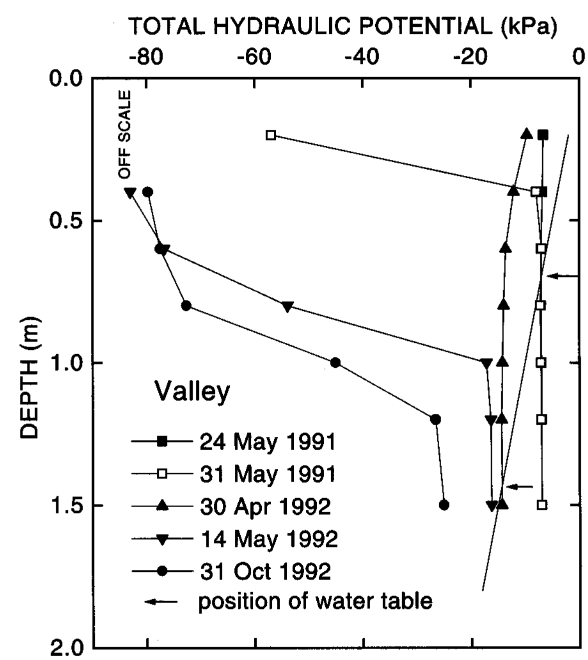


Fig. 11 *Valley, profiles of total hydraulic potential in the 1990–91 wet season (24 and 31 May), the 1991–92 wet season (30 April 1992) and the 1992 dry season (14 May and 31 October).*

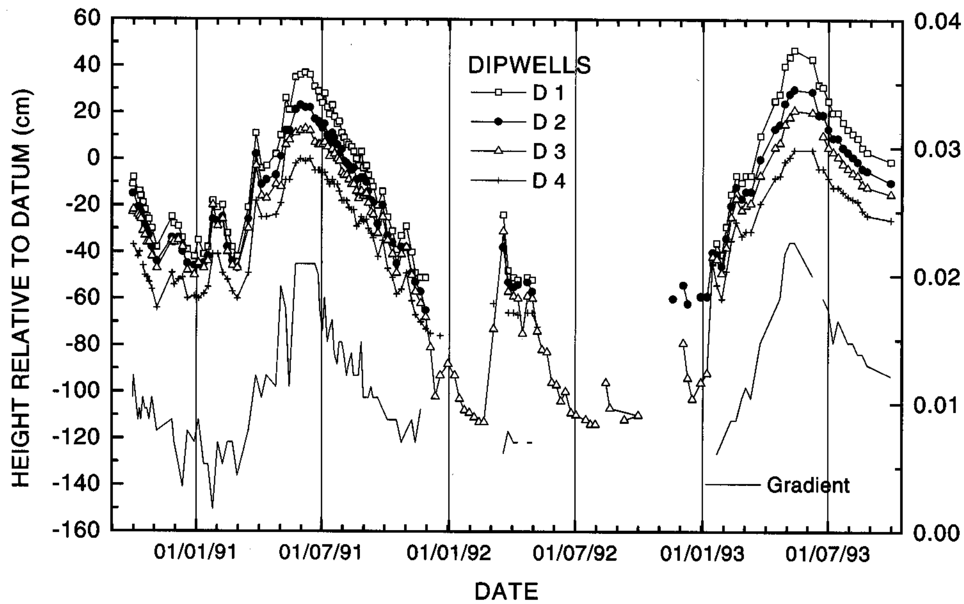


Fig. 12 *Water levels for 4 dipwells in sequence down the foot of the slope to the valley floor (D4) between September 1990 and September 1993. Levels are expressed relative to a valley floor datum. The water table gradient between D1 and D3 is also shown.*

# Discussion

PLATEAU AND SLOPE

The soil water storage behaviour on the plateau and slope was remarkably similar, in terms of overall storage changes (Fig. 2), standard deviation of maximum storage changes (Table 1), dry season evapo-transpiration (Fig. 5) and the low variability of the advance of the wetting front on the plateau (Fig. 9). This is surprising in view of the variability of throughfall (Lloyd and Marques, 1988) and the uneven tree distribution which might lead to considerable variability of uptake. Hodnett *et al.* (1995) have indicated that the inherent variability of soil water availability is low. For the soil water storage behaviour to be so similar on plateau and slope, all of the processes influencing the soil water storage must be almost identical in both areas.

Soil water uptake was identical on both plateau and slope (Fig. 5); if it is the same throughout the year, then drainage losses should also be the same. On the slope, the 'drainage' loss determined from the water balance is the net result of surface runoff, interflow and deep drainage, all of which are rapid processes (probably within 12 h of an event) and it is not readily possible to separate their effects on the soil water storage (measured weekly). Runoff could occur at any time of year during storms of sufficient intensity, but significant deep drainage occurs only after the profile has been fully wetted. Any reduction in infiltration as a result of runoff on the slope should be apparent in the storage data after dry season and early wet season storms. There was no evidence of this, despite slopes of 18%. Nortcliff and Thornes (1984) measured negligible runoff on a hillslope plot on similar soils and concluded that 'most of the losses were due to deep percolation and to evapotranspirational losses'.

On the slope, interflow may be an important mechanism for transporting water rapidly to the floodplain. The minimum observed in the water content profiles between 0.4 m and 1 m on the plateau and slope (Fig. 9) is also seen in the adjacent pasture. This layer has a high porosity in the micro and meso-pore range and a very high saturated conductivity, and overlies a zone with a much lower conductivity (Tomasella and Hodnett, 1996). It was also observed that, following saturation by ponding water on the plot, the zone of saturation drained within 5 hours of the cessation of irrigation (cf. Fig. 10). Bonell (1993) has suggested that the relatively low saturated conductivity measured by Nortcliff and Thornes (1984) at a depth of 1 m at the Reserva Ducke site may act as a 'throttle' layer and lead to a saturated zone developing above it in heavy rainfall conditions. At the site of the present study, this layer is clearly a potential interflow route under conditions of prolonged and intense rainfall. However, saturated conditions are unlikely to persist for long because of vertical drainage through the underlying layer. As a result, interflow will be very transient process. The strongly porous layer is a characteristic feature of these soils (Chauvel, 1982). The interflow process itself may, in part, contribute to its creation, together with the faunal and mineralogical processes discussed by Chauvel *et al.* (1987).

VALLEY

In the valley, the processes controlling the depth of the water table play a key role in determining the seasonal soil water storage changes. Figure 9 shows that the soil profile on the plateau (and presumably the slope also) wets up with a well defined wetting front. Early in the 1990–91 wet season, the generally decreasing water levels and gradient (Fig. 12) indicated that recharge was occurring through the floodplain, but that little or no recharge reached the water table from beneath the plateau and slope. Although storage in the 2 m profile on the plateau and slope had reached a typical wet season value by December 1990, the water table gradient began to increase steadily only in March 1991, suggesting that only then had the deficit in the profile below 2 m been replenished, permitting recharge to commence beneath the slope and plateau areas. These data also imply that recharge by by-pass flow in macropores is probably not an important process at this site.

The lag between the maximum plateau profile storage in early May and the maximum water table level in June implies a transit time of about 1 month for drainage pulses to pass through the deep unsaturated zone and for the water table at the foot of the slope to respond to this recharge input. After the water table had reached its maximum level, the gradient decreased through the dry season as the groundwater storage beneath the plateau and slope discharged beneath the floodplain to the stream. This discharge maintains the water table close to the valley floor and sustains streamflow (albeit declining) throughout normal dry seasons. These results support the observation by Nortcliff and Thornes (1984) that the water level in the floodplain is sustained by vertical recharge through the hillslope (and plateau) areas.

The effect of the decreasing discharge of water from beneath the hillslope was also shown by the increase in valley floor soil water depletion rates as the storage declined (Fig. 4). When the water table was within 0.3 m of the surface, the very low soil water depletion rates (0.5 mm day$^{-1}$) indicated that the groundwater discharge was contributing as much as 3.3 mm day$^{-1}$ to forest water uptake. After December 1991, when the water table reached 1.0 m, there was a very marked decrease in water level (Fig. 12, Dipwell 3) and valley floor storage (Fig. 2) as the forest began to rely mainly on soil water storage. The stream dried up in late 1991 (probably a fairly rare event) but a small groundwater gradient from beneath the hillslope remained; this must have maintained a small groundwater flux contributing to valley floor forest soil water uptake.

LONG-TERM CONTEXT OF THE DATA

Hodnett *et al.* (1996b), examined the soil water storage data from the Fazenda Dimona site in the context of a longer term record predicted using the daily rainfall data from Reserva Ducke for the period 1966–1992. The analysis showed that a deficit of 210 mm developed below 2 m on the plateau by February 1992 and that a larger deficit occurred only once in the predicted 27 year series. The very close similarity of soil water behaviour on the plateau and slope suggests that a similar deficit would have developed under the slope. As a result of the large deficit and the late onset and low rainfall of the 1991–92 wet season, there was very little recharge. Conditions during late 1991 and through 1992 were clearly not typical of 'normal' conditions but did provide a valuable insight into the soil water behaviour that would result in different parts of the landscape if climate change led to longer dry seasons. The lack of recharge from beneath the plateau and slope in 1991–92 had a very pronounced effect on the valley floor soil water storage throughout the following year, until a large amount of recharge from November 1992 to May 1993 restored more 'normal' conditions.

## Summary and conclusions

PLATEAU AND SLOP

There was virtually no difference in the soil water storage changes on the plateau and slope, regardless of season, suggesting that the water balance processes affecting soil water storage were similar in both landscape units. The data suggest that the forest was able to use all of the water available in the upper 2 m of the profile. The maximum storage changes recorded in the 2 m profile were 154 mm and 159 mm on the plateau and slope respectively, confirming the very low soil water availability shown by other studies on similar soils in the area. Seasonal changes of water content below 2 m depth were only 0.02–0.03 MVF. On the plateau, water was taken from below 3.6 m and the results imply that this also happened on the slope. The similarity of behaviour means that, for modelling purposes, the plateau and slope areas may be treated as one.

Surface runoff was not observed on the plateau or slope. In the early wet season, the plateau soils wet up with a well defined wetting front, and bypass flow does not appear to be an important recharge process. Deep drainage (groundwater recharge) appears to occur beneath the plateau and slope only after the profile has been rewetted to a typical wet season condition (restoring a downward gradient of hydraulic potential throughout the profile and raising the unsaturated conductivity).

VALLEY FLOOR

Except during 1992, changes in storage on the valley floor were dominated by the water table, which varied between 0.1 m and 0.8 m of the soil surface at the end of the wet and dry seasons respectively. This limited the range of storage change to about 50 mm; soil water uptake by the forest was largely replenished by groundwater discharge from beneath the plateau and slope to the stream. The groundwater contribution to uptake varied inversely with the depth to the water table, from an estimated 91% with the water table at 0.45 m to 23% with the water table at 1.69 m.

The small soil water storage changes are typical of most years because, although the groundwater discharge varies through the year, it rarely ceases. The discharge is dependent on the timing and amount of deep drainage from beneath the plateau and slope areas. There was a marked lag between the replenishment of the plateau and slope storage and the start of the increase in groundwater gradient towards the valley. In 1991–92, which was exceptionally dry, there was little recharge beneath the plateau/slope. As a result, the valley floor water table remained below 0.8 m throughout 1992 and the forest then used stored soil water, resulting in much larger storage changes. The minimum storage occurred completely out of phase with the plateau storage. At the end of the wet season, maximum water levels, and storage, occurred about a month after maximum storage was observed on the plateau.

The amount of water available for evaporation by vegetation is normally controlled by the rainfall, the evaporation and the soil properties but, in the valley, there is an additional lateral contribution from groundwater. In particular, this may need to be taken into account in GCM formulation, because in dry periods, the plateau and slope areas may suffer soil water stress whereas the vegetation in the valley floor may not. This may be particularly the case for shallow rooted vegetation such as pasture. The depth of the water table in the valley floor, and the recharge processes that control it, will have a significant influence on the generation of storm runoff.

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