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Water storage and runoff processes in plinthic soils under forest and pasture in Eastern Amazonia

Jorge M. de Moraes,[1,2]* Azeneth E. Schuler,[3] Thomas Dunne,[4] Ricardo de O. Figueiredo[5] and Reynaldo L. Victoria[1]

[1] *Laboratório de Ecologia Isotópica, Centro de Energia Nuclear na Agricultura, Universidade de São Paulo, Brazil*
[2] *Departamento de Engenharia Ambiental, Escola de Engenharia de Piracicaba, FUMEP, Brazil*
[3] *Instituto de Pesquisa Ambiental da Amazônia, Belém, Brazil*
[4] *Donald Bren School of Environmental Science and Management, University of California, Santa Barbara, USA*
[5] *Empresa Brasileira de Pesquisa Agropecuária, CPATU Amazônia Oriental, Belém, Brazil*

Abstract:

Extensive areas of the Amazon River basin are underlain by soils with shallow impeding horizons. To evaluate how the distinctive hydraulic properties of soil with a plinthic horizon under forest and pasture affect water storage and runoff process, two first-order catchments drained by ephemeral streams were instrumental in eastern Amazonia. Field measurements showed the presence of a strong vertical gradient of saturated hydraulic conductivity, which declines to extremely low values (median <1 mm h^{-1}) at the plinthite layer, limiting both vertical and lateral flow, and keeping the soil water content close to saturation throughout most of the wet season. This scenario led to the frequent occurrence of saturation overland flow (SOF) under both land covers and very small amounts of shallow sub-surface flow (SSF). The annual flow in the exit channels was 3·2% of throughfall (2·7% of annual rainfall) under forest and 17% of annual rainfall for pasture, while the frequency of days with overland flow (OVF) was about 60% of the days for both catchments during the wet season. In the forest, all OVF originated from saturated areas, while in the pasture, infiltration-excess OVF accounted for 40% of the runoff and SOF accounted for 55% of runoff. The higher flow generation in the pasture could be explained by the higher water storage compared to the forest, promoting more frequent SOF, and additionally by the lower hydraulic conductivity near the surface favouring the occurrence of Horton overland flow (HOF). Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS runoff processes; overland flow; water storage; hydraulic conductivity; tropical rainforest; pasture; plinthic soils

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INTRODUCTION

Large areas of the Amazon basin are underlain by soils with strongly developed impeding horizons. In some places, these soils are classified as podzols or latosols (ultisols and oxisols, respectively, in the US soil taxonomy) with a distinctively dense, clay horizon, while in others, this horizon is sufficiently cemented and indurated for the soil to be classified as 'plinthic'. Sombroek's (1984) survey of the predominant soils of the Amazon region, categorized 'plinthic' and 'podzolized' as the two main types of imperfectly drained soils. He observed the occurrence of these soils on flat parts of late Cenozoic terraces and piedmont plains in the fringe areas of the crystalline shields. The hydraulic characteristics of these soils, and their effect on water storage and runoff processes have not been studied in the Amazon region. The hydrologic functioning of these soils has been altered in recent decades by land-use changes involving extensive replacement of primary forest by pastures, typically grazed at stocking densities of $\sim$1 cow ha^{-1} $year^{-1}$, and partial recovery of the

* Correspondence to: Jorge M. de Moraes, Laboratório de Ecologia Isotópica, Centro de Energia Nuclear na Agricultura, Universidade de São Paulo, Av. Centenário, 303, 13400-000, Piracicaba, Brazil. E-mail: jmmoraes@cena.usp.br

woody vegetation (*capoeira*) in some abandoned pastures (Gash *et al*., 1996; INPE, 2000; Nepstad *et al*., 1999).

Land-cover changes and their interactions with the hydraulic structure of soils with impeding layers alter evapotranspiration, soil moisture content, groundwater recharge, runoff processes, and river flow. The resulting hydrologic changes affect water resources and biogeochemical processes supplying chemicals to stream channels (Biggs *et al*., 2002, 2004; Neill *et al*., 2001), and losses of sediment (Nortcliff *et al*., 1990) and associated nutrients (Ross *et al*., 1990).

Replacement of the deep-rooted native forest with shallow-rooted pasture has disturbed the hydrological cycle in many areas of Amazonia (Gash *et al*., 1996). Removal of forest decreases interception and evapotranspiration (Wright *et al*., 1996), increases soil moisture levels (Hodnett *et al*., 1995) and groundwater recharge (Jipp *et al*., 1998), decreases infiltration capacity and soil water storage capacity of the upper root zone, and increases both quickflow (in this case overland flow (OVF)) and delayed flow (sub-surface flow (SSF)) to various degrees that depend on the land-cover history.

The runoff response of a catchment is controlled predominantly by rainfall regime, topography, vegetation, and soil hydraulic properties (Dunne, 1978). Bonell and Balek (1993) highlighted the differences in these driving variables between temperate landscapes and the humid tropics, where, for example, predominantly clay-rich soils, and high precipitation intensities can generate extensive saturation overland flow (SOF) where an impeding layer exists near the surface. This combination also suggests that disturbance arising from forest conversion could extend the impeding layer to the surface, favouring the occurrence of infiltration-excess OVF as well as SOF.

We monitored the hydrology of two first-order catchments, drained by ephemeral streams in eastern Amazonia, to understand how the distinctive hydraulic properties of soil with a plinthic horizon under forest and pasture effect: (1) water storage changes, (2) groundwater recharge, (3) evapotranspiration, and (4) the volume of water leaving hillslopes by various flow paths, especially the delivery of water by quickflow overland to first-order channels. One catchment drains primary forest, and the other drains a pasture. We also made some measurements of soil properties in an abandoned pasture (*capoeira*) to indicate the rate at which soil properties changed during the regeneration of a woody plant cover.

STUDY SITE

The study was located on Fazenda Vitória, a cattle ranch 6 km north of the town of Paragominas (2°59′ S, 47°31′ W) in Pará state, Brazil (Figure 1). This region was settled in the early 1960s (Nepstad *et al*., 1991), and the ranch is a patchwork of mature forest, pasture, logged forest, and second-growth forest on abandoned pasture land (*capoeira*).

Mature forest on the Fazenda Vitória is species-rich, closed-canopy, and evergreen (Leaf Area Index (LAI) = 5–5·5 and above-ground biomass = 300 t ha^{-1}). The canopy had an average height of 30 m with some emergent trees reaching 45 m. Pastures were originally cleared in the late 1960s and planted initially with *Panicum maximum*, which was partially replaced with *Brachiaria humidicola* by 1990 (Jipp *et al*., 1998). The mean cattle stocking density in pasture was about 0·8 head ha^{-1}. At the beginning of the study, the *capoeira* had been regenerating for 12 years.

Mean annual rainfall in the region (1973–2003) was 1760 mm $year^{-1}$, ranging from 878 to 2766 mm with strong seasonality (<16% of the annual total falls in June–November). The inter-annual variability is driven mainly by the El Nino-Southern Oscillation (Jipp *et al*., 1998). At a site with a deep latosol and no plinthite within the upper 8 m, Jipp *et al*. (1998) computed mean annual actual evapotranspiration (ET) values of 1515, 1370, and 1480 mm $year^{-1}$ for the mature forest, pasture, and *capoeira*, respectively, over 4 years of measurements (1991–1994). Even in the driest years, rainfall exceeds ET during the wet season, but the duration and intensity of annual drought forces vegetation to tap moisture through roots >1 m deep during

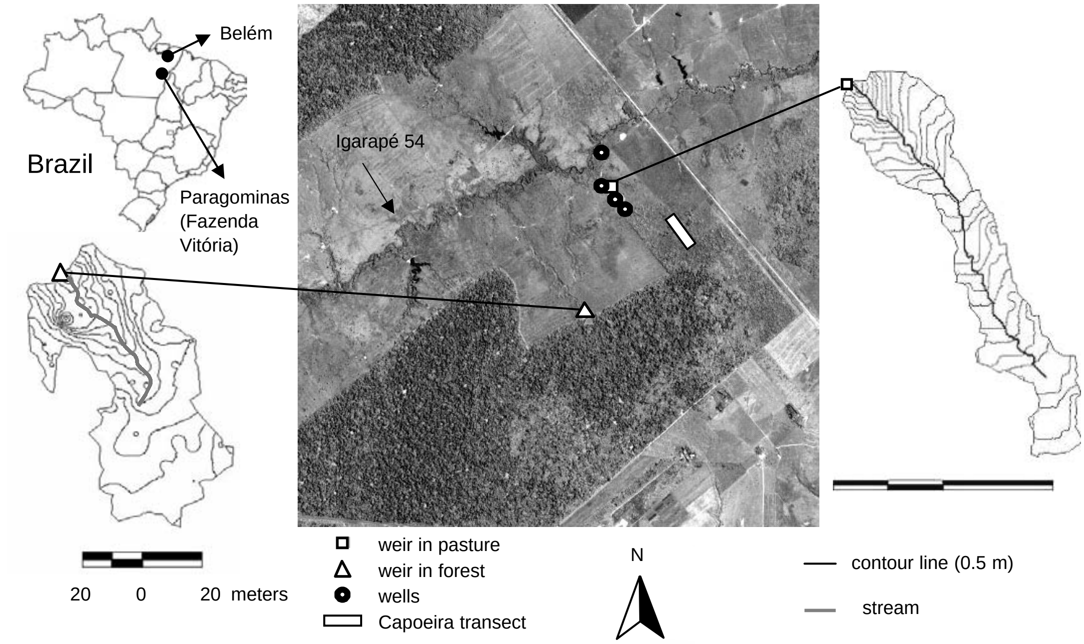

Figure 1. Location of Paragominas in eastern Amazon, satellite image (IKONOS) of the Fazenda Vitória, and topographic maps of the catchments

several months each year, allowing trees to continue photosynthesis and transpiration during the long, dry season (Jipp *et al*., 1998).

The topographic and hydrogeologic characteristics of the site were representative of a wide region. The study was located on the sideslopes of a 60-m high Pleistocene river terrace (Sombroek, 1966; Clapperton, 1993); the side slopes have an overall gradient of 0·02–0·03 (Figure 2). The central part of this slope, with a gradient of approximately 0·05, was fretted into first-order catchments with depths of 1–2 m, widths of 30–40 m, separated by relatively planar, 300-m wide slopes. The catchments were drained by ephemeral channels, two of which we have gauged (Figures 1 and 2). The depth of the regional water table varied from more than 45 m below the upper terrace level to 11–21 m beneath the ephemeral channel beds of the monitored first-order basins during the dry season, and to the surface at the perennial stream, Igarapé Cinquenta e Quatro, which has a drainage area of approximately 100 km^2. The water table receives recharge from the study catchments, but does not affect their hydrology.

The catchments were underlain by a 4–6 m deep, clay-rich soil, developed on the sandier Barreiras Formation and finer colluvium from the overlying Belterra clay. Textural profiles for the upper 120 cm of these soils are shown in Figure 3(a–c). At the higher, forested catchment, the soil was classified by pedologists from EMBRAPA as a well-drained, yellow latosol or Haplustox in the US soil taxonomy (Soil Survey Staff, 1988), consisting predominantly of kaolinite (>70%) and ironstone. It is developed in colluvium from the Belterra clay. At the lower, pasture catchment (PC), the soil was classified as a clay-rich (40–60%) haplic Plinthosol, developed from both clay-rich colluvium from upslope and from the sandier Barreiras Formation. This plinthosol (ultisol in the US soil taxonomy) has a higher sand content, which gradually increases downslope as the plinthite grades from haplic on the upper slope to argiloluvic on the lower midslope. Clay content increased at 40–60 cm depth, at which the plinthite fragments usually appear, and then from 60 to 90 cm, clay content decreases again, despite a more visible and coherent plinthite that makes digging difficult. Below the first metre, sand content increased with depth in the pasture, ranging from 20 to 35% at 1 m depth to more than 60% for depths greater than 10 m midway between the plateau and the

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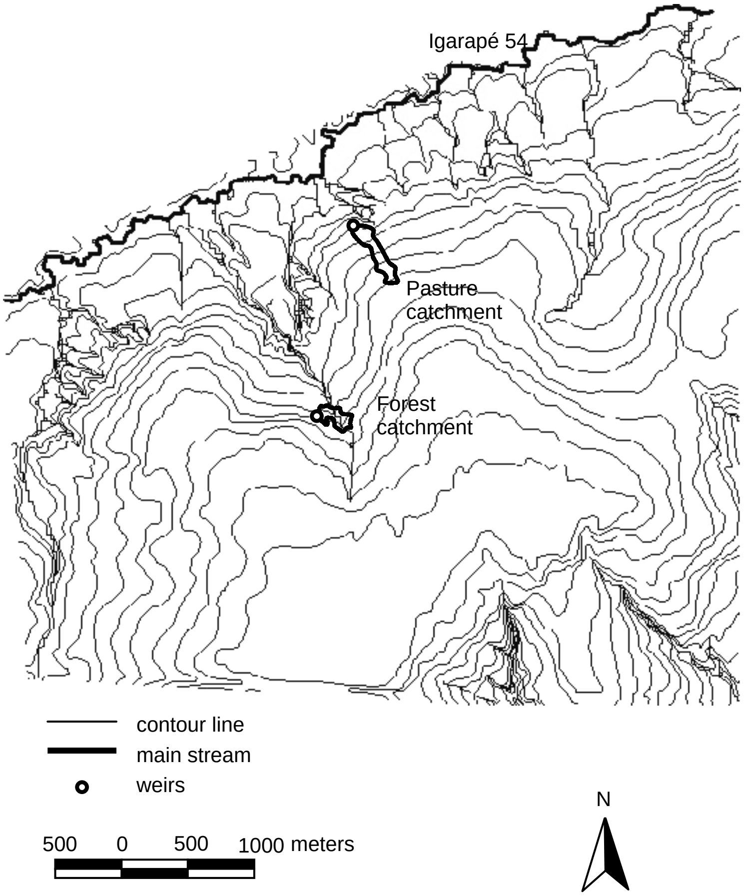

Figure 2. Topographic map of the whole landscape Fazenda Vitória (5 m contour interval), illustrating the main stream (Igarapé 54) and the monitored catchments

stream (Figure 3(d)). These measurements diverged from the commonly perceived notion of clay-rich oxisols in this landscape, although the results were consistent with the fluvial-lacustrine sediments common along the Amazonian floodplain areas (D. Markewitz, University of Georgia, personal communication).

The plinthite depth varied from 9 to 10 m at the top of the plateau, decreasing gradually downslope to reach the soil surface between 40 and 60 m upslope of the Igarapé Cinquenta e Quatro. At the monitored catchments, the maximum clay at 40–60 cm in each of the profiles (Figure 3) corresponded to the beginning of the plinthite layer. The soil layer above the plinthite is generally a few centimetres thick near the ephemeral channels and increases abruptly to an almost constant depth of about 0·9–1·0 m elsewhere. The plinthite under the forest contained more clay and is less indurated than under the pasture. We demonstrate that despite the differing soil classifications between the two sites, their hydraulic characteristics are very similar.

METHODS

We monitored a first-order forested catchment (area 0·33 ha; mean slope 0·09), and a pastured catchment (area 0·72 ha; mean slope 0·06) (Figure 1). Figure 4 illustrates the equipment installed in both the catchments. Rainfall was measured continuously with tipping-bucket rain gauges at the top of the plateau, 300 m SE of

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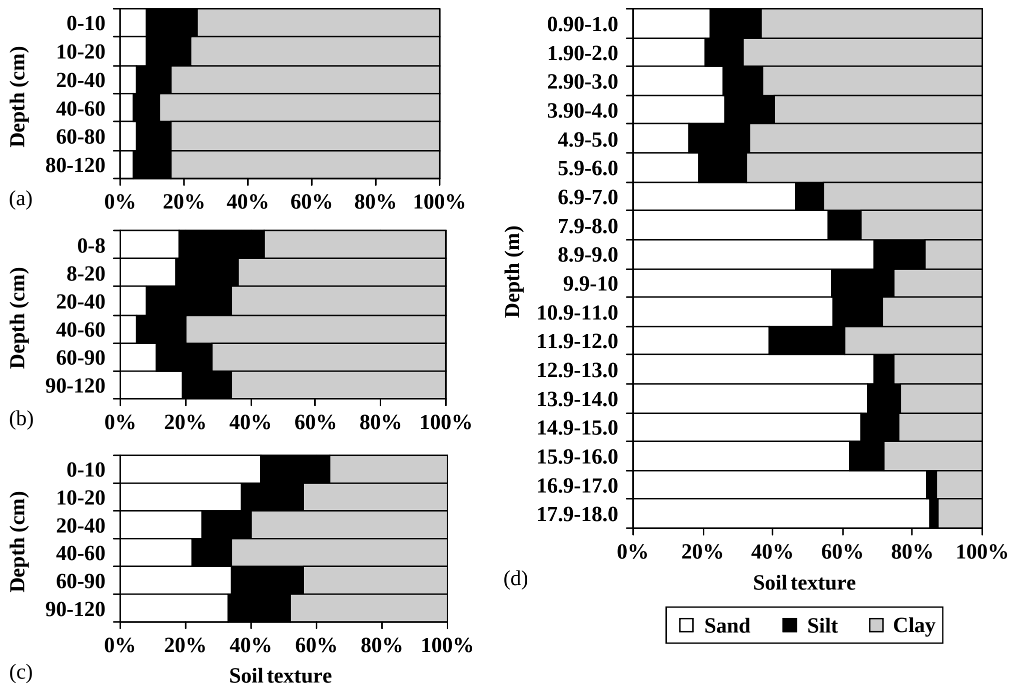

Figure 3. Soil particle versus soil depth at four sites: (a) upslope, forested catchment, (b) upper middle slope, (c) lower middle slope, both in the pasture catchment, and (d) middle slope from 1 to 18 m depth at the pasture catchment

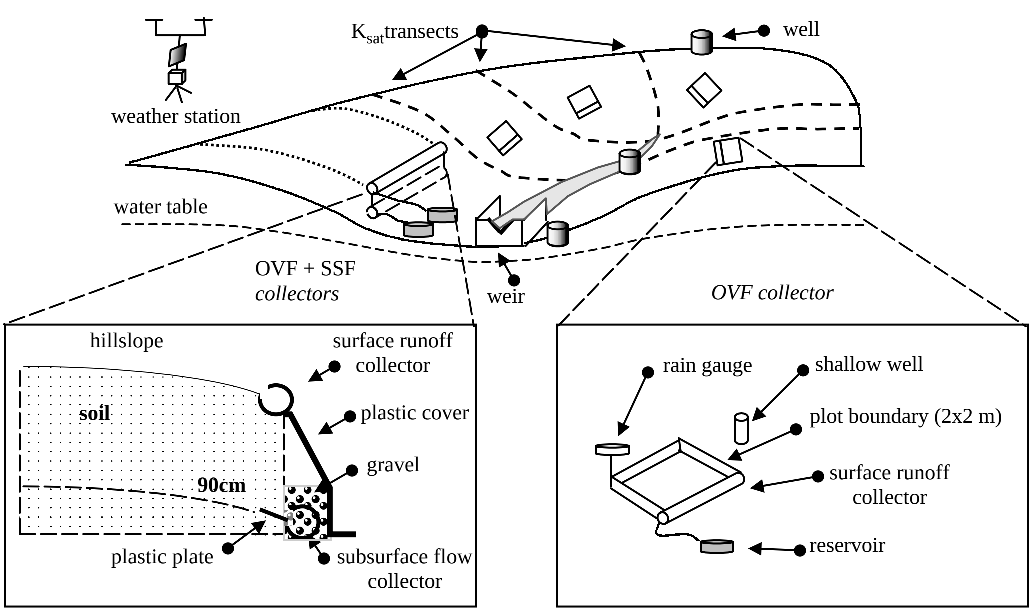

Figure 4. Schematic of the field measurements in the pasture and the forest catchments

the PC, and 50 m from the mouth of the forest catchment (FC). Six rain gauges were installed inside the FC and randomly repositioned each week along the two transects to estimate throughfall.

Streamflow was recorded every 15 min at a 90 °V-notch weir equipped with a water-level recorder in each catchment. OVF was measured in four 4 m^2 plots: two on gentle slopes and two on steeper slopes. The slopes of these plots in the pasture were 0·20, 0·17, 0·09, and 0·06, and in the forest 0·21, 0·21, 0·16, and 0·15. They were monitored daily in four wet seasons from 2000 to 2003. An assembly of 2-m wide troughs for measuring OVF and SSF was installed in a pit draining a 10-m long hillslope in FC (20 m^2 of drainage area) and 12-m long hillslope in PC (24 m^2 of drainage area). The SSF collector was installed at 0·9 m depth, immediately above the plinthite. The average gradient of the short slopes draining to these troughs were 0·30 and 0·28 for FC and PC, respectively. Water-table depths were monitored daily during the wet season and biweekly during the dry season, in a set of three wells (11, 18, and 21 m depth) positioned along the axis of the PC. Besides the deep water table, which was 11 to 21 m below the PC, a shallow perched water table was observed daily in a set of 1 m deep wells, monitoring the variation of saturated soil sub-surface zone in FC and PC (Figure 4). The soil tension variation was measured with standard tensiometers, each one composed of a plastic tube, ceramic cup, and vacuum manometer. For both studied catchments, tension was monitored daily during the 2002 and 2003 wet seasons by five sets of tensiometers: four next to the OVF 4 m^2 plots, and one next to the SSF trough. Each set included four tensiometers installed at 0·15, 0·3, 0·6, and 0·9 m depths.

Vertical profiles of saturated hydraulic conductivity (K_{sat}) were measured at 10 or 25 m intervals along four interfluve-to-channel transects in each catchment (Figure 4), using a Guelph Permeameter (Soilmoisture Equipment Corp., Santa Barbara) over depth increments of 0·05–0·15, 0·20–0·30, 0·40–0·50, and 0·80–0·90 m. Soil cores were collected at 0·20 m and 0·80 m ($n = 6$ at each depth) in each catchment to determine bulk density and water retention curves.

RESULTS AND DISCUSSION

Precipitation

Average annual (October–September) precipitation was 1769 mm in the period 2000 to 2003. The frequency distribution of 15-min rainfall intensities is summarized in Figure 5. The average storm duration was 2·3 h, higher than the value of 1·8 h reported by Lloyd (1990) near Manaus. The fraction of rain falling after noon was 92% with 68% falling after 18:00 h. Throughfall averaged 87% of total rainfall, similar to the 86% measured by Ubarana (1996), around 300 km south of Paragominas, and within the range of values 80% and 91% recorded by Franken *et al*. (1992) and Lloyd and Marques (1988), respectively, at Reserva Ducke, near Manaus.

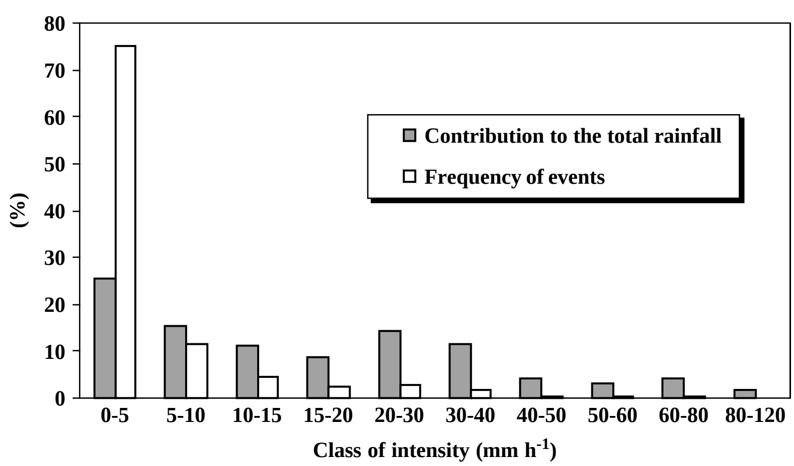

Figure 5. Frequency distributions of the 15-min rainfall intensity and percentage contribution to the total rainfall for years 2000–2003

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Soil profile characteristics

Porosity was derived from moisture retention data, considering pressures below −30 kPa to be representative of micropores where water dynamics were dominated by matric pressure gradients (Luxmoore, 1981). In this study, meso- and macro-porosity are together indicated by pressures above −30 kPa, characterizing pores where water drainage is dominated by gravitational forces. Meso- and macro-porosity was 16% in the forest and 8% in the pasture at 0·2 m depth, while at 0·8 m depth the values were 9 and 6%. At both FC and PC, the mean total porosities of the upper 0·8 m were 49 and 48% respectively, and the mean bulk density values were 1·32 and 1·38 g cm^{-3} respectively ($n = 6$ at 0·2 m and $n = 6$ at 0·8 m under each cover). These values were similar to those measured in podzols under both forest and pasture in Rondonia by Tomasella and Hodnett (1996) and in Pará by Hodnett *et al*. (1996), but higher than those of the central Amazonian oxisols reported by Hodnett *et al*. (1995).

The value of K_{sat} decreased sharply at a shallow depth even under forest, with median values ranging from 230 mm h^{-1} near the surface to 17 mm h^{-1} at 0·20–0·30 m and to 0·7 mm h^{-1} at 0·80–0·90 m (Figure 6). Under pasture, K_{sat} had a median of 4 mm h^{-1} near the surface, which increased slightly at depths of 0·20–0·50 m to around 5 mm h^{-1}, and then decreased sharply to 0·05 mm h^{-1} at 0·80–0·90 m. Occasional high values indicate the effects of macropores, especially in the upper 0·5 m, and the effect was much larger in the intact forest soil. Under pasture, the collapse of macropore structure was particularly evident in the upper 0·2 m. Under *capoeira*, median K_{sat} decreased abruptly from 14 mm h^{-1} near the surface to 1 mm h^{-1} at 0·20–0·30 m and 0·3 mm h^{-1} at 0·80–0·90 m, indicating that recovery of K_{sat} was slight after 12 years of colonization by weeds and woody vegetation. The layer with the lowest and least variable K_{sat} values occurred around 0·80–0·90 m in all covers. In the PC and FC, the low K_{sat} zone was related to a dense plinthite horizon, whereas in the degraded pasture, it was caused by a compacted clay stratum.

The strong vertical gradients of K_{sat} differed from measurements in oxisols near Manaus in central Amazonia (Franken and Leopoldo, 1986/1987; Nortcliff and Thornes, 1989; Lesack, 1993) where the hydraulic properties changed only weakly with depth. Strong anisotropy was also found in the state of Rondônia, southwestern Amazonia, under oxisols (Elsenbeer *et al*., 1999). We did not measure the infiltration capacity of the surface at Fazenda Vitória, but in Rondônia, we have measured infiltration capacities in pasture ranging from 12 to 28 mm h^{-1} with a tension infiltrometer (Elsenbeer *et al*., 1999). Safran and Dunne (unpublished) also used a small sprinkling infiltrometer to measure values of 150–180 mm h^{-1} under forest near Porto Velho, Rondonia, and 18–20 mm h^{-1} in a 10-year-old pasture nearby.

Soil- water tension

Soil tensions remain in the range 0–10 kPa during most of the wet season in both catchments, often throughout the profile (Figure 7). Dry periods of up to 5 days duration and the end of the wet season caused rapid desiccation to tensions as great as −40 kPa, beginning near the surface and decreasing with depth. This effect was much more pronounced in the forest, suggesting that water uptake by roots played an important role in the profile changes. At the 0·3 m and 0·6 m depths, tension values indicated that desiccation was limited to the meso/macro porosity during rainless periods, suggesting that gravitational drainage was compensating for root uptake, and at 0·9 m, the tension remained above −10 kPa in the forest and above −5 kPa in the pasture almost throughout the entire wet season.

From soil tension during 2002–2003 wet season, soil moisture was calculated using the Van Genuchten equation (Van Genuchten *et al*., 1991), for which parameters were estimated from soil retention curves of six samples at two depths (0·2 and 0·8 m), as shown in Table I. An estimate of the wet season average soil moisture values for all monitored depths showed that the soil under forest was generally drier than that under pasture, and the differences between forest and pasture values were greater at 0·15 and 0·30 m depths.

These results agreed with the findings of Hodnett *et al*. (1996) who pointed out that larger seasonal variation of water storage beneath the forest compared to pasture, under different soils types, and precipitation regimes in Amazon. Ross *et al*. (1990), compared water tension in undisturbed forest, partially cleared, and totally

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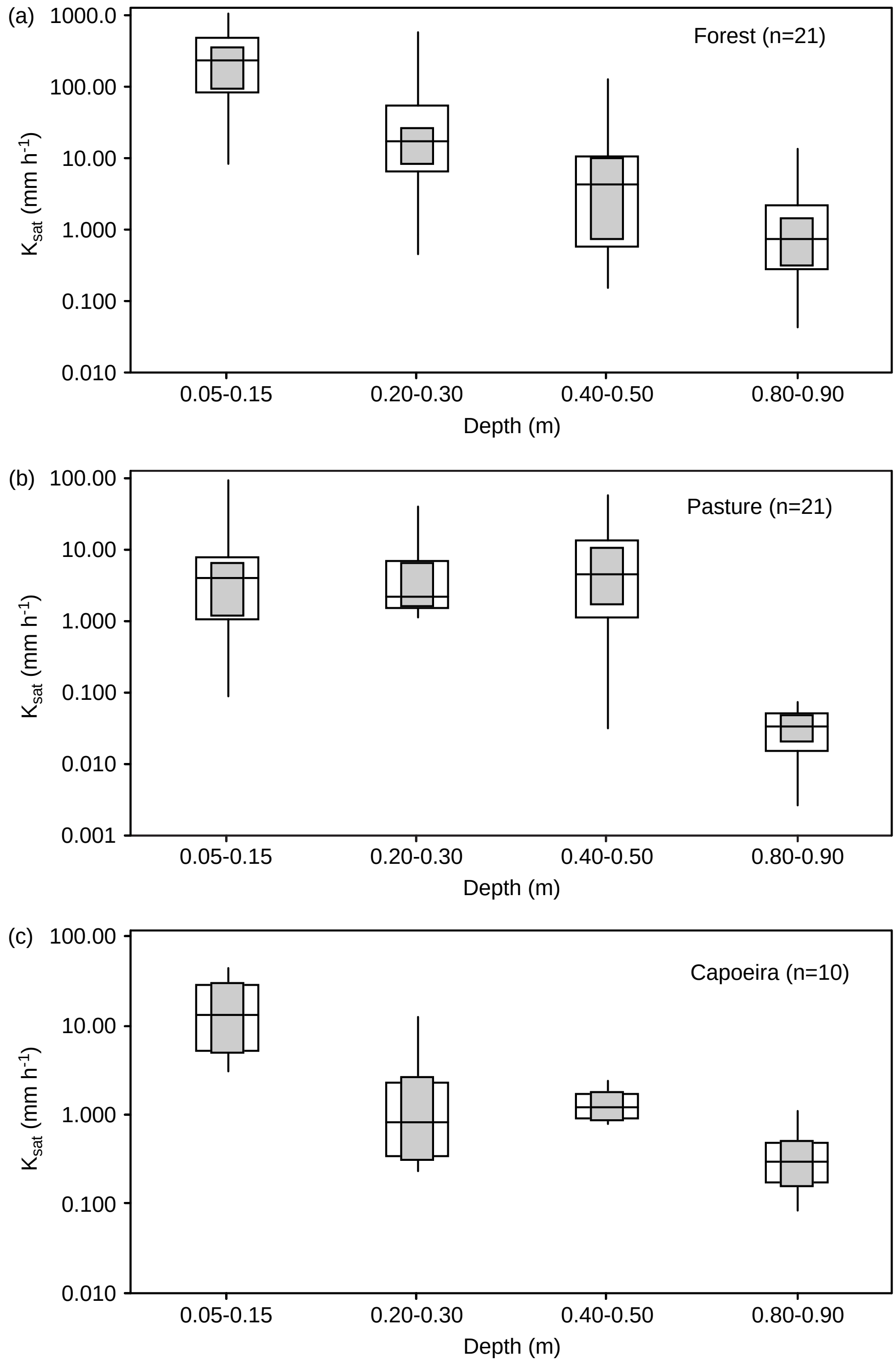

Figure 6. Box-plot results of K_{sat} as a function of depth, under forest (a) pasture (b) and (c) *capoeira*. The length of the white box represents the sample interquartile range, the cross bar in the box is the sample median and the grey box indicate the 95% interval for the median. The outlying data points defined as being further away from the quartiles than 1·5 times the interquartile range were omitted for clarity

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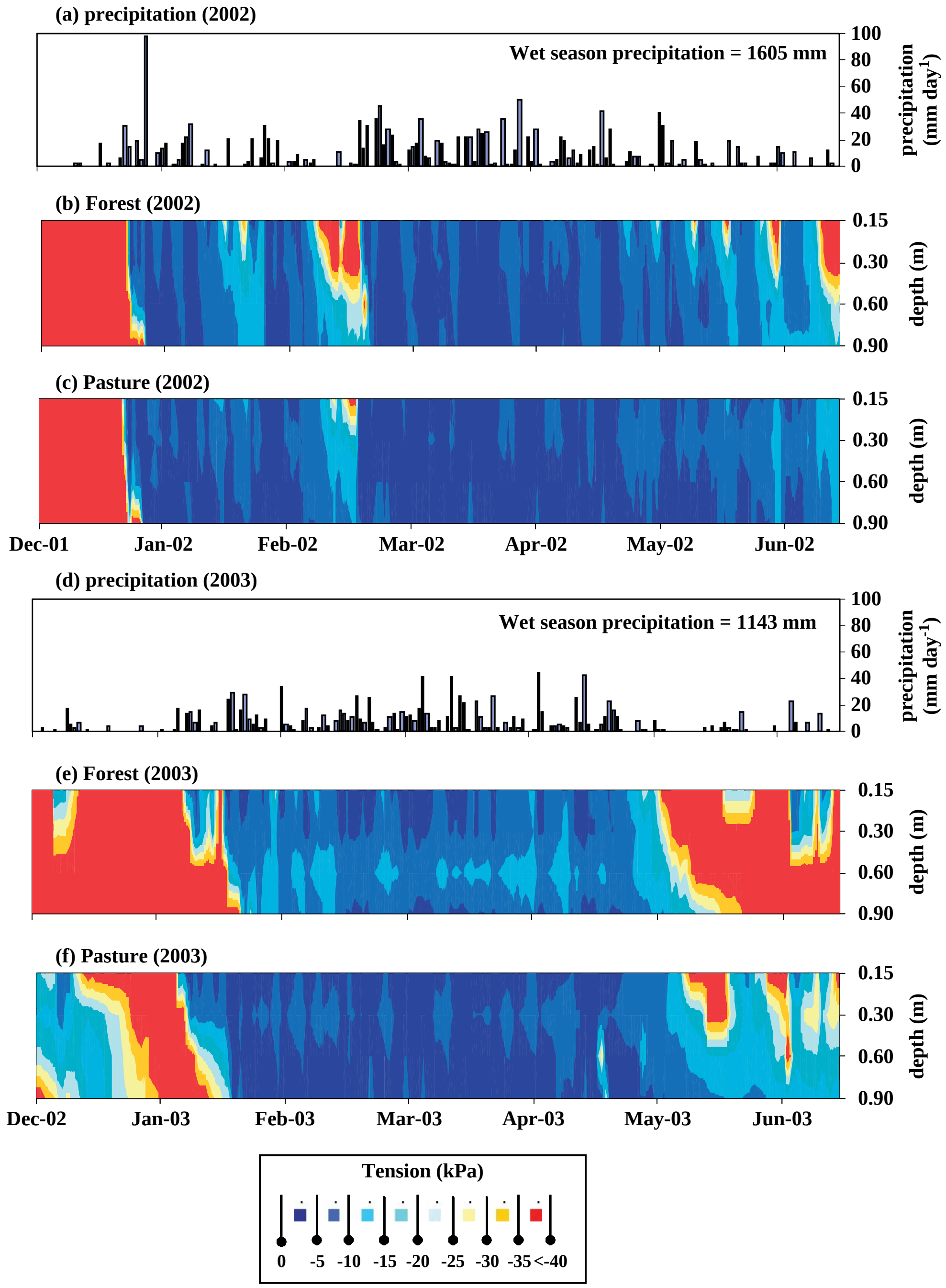

Figure 7. Daily precipitation and soil tension (kPa) corresponding to the 2002 and 2003 wet seasons

cleared plots, installed in a soil where a sandy textured horizon overlies a clay textured layer which, in turn, was underlain by laterite at depths of about 1–1·2 m. Our results agree with that study in two ways. They showed first the influence of the land cover, where the highest tensions were found under the undisturbed

Table I. Mean values of Van Genuchten parameters fitted from retention data of the forest catchment (FC) and pasture catchment (PC). Standard deviations are presented in parenthesis

	α (m^{-1})	θ_{sat} ($cm^3\ cm^{-3}$)	θ_r ($cm^3\ cm^{-3}$)	n	m
PC—0·20 m	7·4 (5·6)	0·47 (0·01)	0·35 (0·05)	1·346 (0·041)	0·256 (0·022)
PC—0·80 m	3·5 (1·5)	0·49 (0·03)	0·37 (0·02)	1·390 (0·072)	0·279 (0·035)
FC—0·20 m	21·6 (14·6)	0·48 (0·05)	0·28 (0·07)	1·366 (0·021)	0·268 (0·011)
FC—0·80 m	5·9 (3·5)	0·48 (0·03)	0·32 (0·05)	1·405 (0·046)	0·288 (0·023)

forest plot, and second, the effect of the soil structural features, particularly the presence of lateritic layer favouring soil saturation over this impeding layer and consequently the occurrence of SOF.

Water-table depth

Water-table depth, measured in a well located at the mouth of the PC, ranged from 9·5 m in the dry season to 10·8 m in the wet season with a lag of several weeks between rainfall and recharge to the water table, although the contributions of local and upslope recharge are not yet known. The other wells located at the middle and the top of the PC, with average water-table depths of 18 m and 21 m, respectively, showed similar behaviours, indicating an almost horizontal water table. The FC water-table depth was not measured, but was estimated from the topographic map to be around 30 m. In both cases, this deep water-table was not involved in the near-surface flow processes in the PC and FC.

Perched water table

Six shallow wells were monitored daily in each catchment during the 2002 wet season. The results showed the occurrence of a perched water-table in the wells for an average of 25 days in the forest and 43 days in the pasture. In those days, water levels varied from 10 to 60 cm below the soil surface in the mornings (i.e. approximately 12 h after rainfall, which provided time for significant macropore drainage that minimized the recorded frequency of saturation). The frequency distributions of depths of the perched water table beneath the two cover types are presented in Figure 8. The higher frequency of saturated conditions under pasture reflected both the lower soil conductivity at shallow depth (Figure 6) and the lower amount of water uptake by roots compared to the forest.

Runoff processes

The soil hydraulic properties and rainfall intensity regime had implications for runoff flow paths in these catchments. Although rainfall intensities (Figure 5) rarely, if ever, exceeded the estimated infiltration capacities in the forest, around 75% of storm-averaged rainfall intensities exceeded the pasture K_{sat} near the surface (Figure 6) and infiltration capacities of 18–20 mm h^{-1} that we have measured in Rondônia pastures, pointing to frequent occurrence of Horton overland flow (HOF). The strong anisotropy of K_{sat} in both soils allowed the development of a perched water table, shallow SSF, and SOF in all surveyed cover types. The particularly low values of K_{sat} at the plinthite level reduce vertical recharge, favouring the surface and near-surface flowpaths. In the Amazon region, studies in the central part of the basin at Reserva Ducke (Nortcliff *et al.*, 1979; Nortcliff and Thornes, 1989; Leopoldo, 2000; Franken and Leopoldo, 1986/1987) and Lake Calado (Williams and Melack, 1997; Williams *et al.*, 1997) have reported the dominance of vertical flowpaths in undisturbed forested areas. Meanwhile, significant lateral flow was reported in thin soil over fractured bedrock under forest at La Cuenca, Peru (Elsenbeer and Lack, 1996; Elsenbeer, 2001) and on Maracá Island, northern Roraima (Ross *et al.*, 1990), where shallow impeding layers were observed.

Volumes of runoff by each near-surface flow path in pasture and forest are shown in Table II for 3 years of measurements (2001–2003). The flow collector in the pasture, which had a capacity equivalent to 12·5 mm

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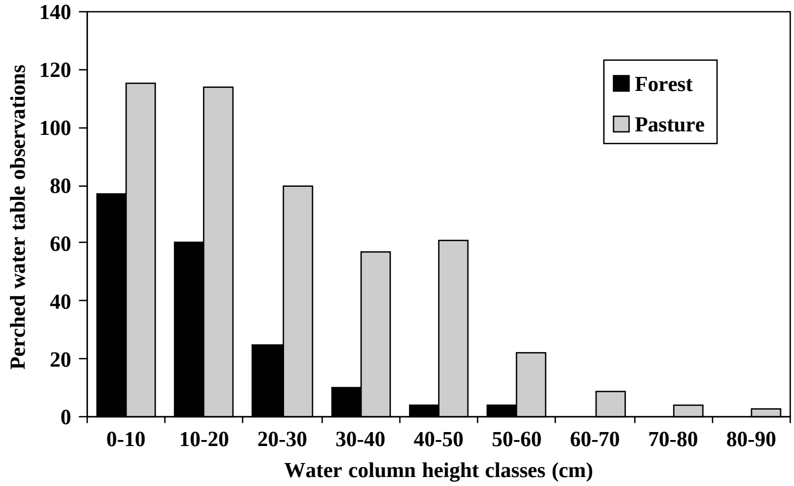

Figure 8. Number of perched water table observations *per* class of water column height (cm) from the bottom of 1-m depth wells in the forest catchment (black column) and in the pasture catchment (grey column), during 2002 and 2003 wet seasons

of plot runoff, was overtaxed in five events (Figure 9). Daily volumes of OVF and SSF plotted against daily values of net rainfall in Figure 9 for the period 2001–2003 indicated that the volume of OVF generation in the pasture was much larger than in the forest. In the forest, no 15-min rainfall intensity exceeded even the lowest of the measured K_{sat} values near the surface, suggesting that HOF was not generated. The high values of infiltration capacity under the FC, and the frequent high moisture content throughout the wet season (Figure 7), indicated that the runoff generating mechanism is SOF. The saturation may have been limited to the upper layers of soil because the average K_{sat} value declined from 230 mm h^{-1} at 0·10 m depth to about 17 mm h^{-1} at 0·25 m depth (Figure 6(a)).

The small quantities of SSF reflected the low K_{sat} values of this soil, even above the plinthite. For example, if the forest soil was fully saturated above the plinthite when SSF outflow rates from a 10-m

Table II. Precipitation (P), overland flow (OVF), sub-surface flow (SSF) in mm, and average ratio flow: precipitation (Q/P) for 2001–2003 wet seasons. In each land cover, values for OVF were taken from four plots and one trough collector and SSF values were taken from a single trough collector

Year	2000 (mm)	2001 (mm)	2002 (mm)	2003 (mm)	Q/P (%) Mean ratio (range)
Total precipitation (P)[a]	1869	2032	1790	1384	
Forest					
P_w—Wet season precipitation[b]	1181	1846	1605	1173	
P_{net}—wet season throughfall	1029	1560	1420	1037	87 (85–88) of P_w
					Q/Pnet
OVF	[c]	51	99	63	5·3 (3·3–6·9)
SSF	[c]	9·0	11	11	0·8 (0·6–1·0)
Pasture					Q/P_w
P_w—Wet season	1188	1520	1605	1112	
OVF	[c]	231	307	247	19 (15–22)
SSF	[c]	12·5	29·4	75	1·4 (0·8–1·8)

[a] Hydrological year (from October of the preceding year to September of the referenced year).
[b] Wet season period (from December of the preceding year to June of the referenced year).
[c] Discarded data.

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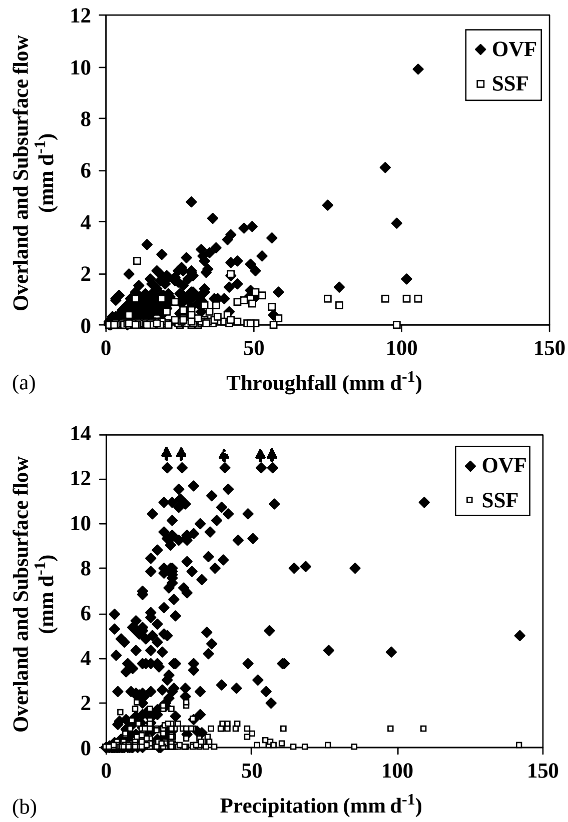

Figure 9. Daily overland flow (OVF) and sub-surface flow (SSF) depths versus daily net precipitation in the forest (a) and in the pasture (b). The values are averages of measurements from all four plots and the trough in each cover type. Five points with arrows indicate minimum values

long hillslope on a gradient of 0·30 were 1 mm d^{-1} (Figure 8(a)), the depth-averaged K_{sat} would be 0·037 m and the transmissivity 0·033 m^2 d^{-1}. If the average measured K_{sat} from Figure 6(a) is regressed against depth [$K_{sat} = 4{\cdot}6 \exp(-7{\cdot}06\ d)$ where d = depth (m); $n = 4$; $r^2 = 0{\cdot}89$], and integrated from 0·9 m depth to the soil surface, the result is a transmissivity value of about 0·7 m^2 d^{-1}, but only a portion of this value would be utilized if the water table drained out of the uppermost soil layer soon after the end of rainfall (Figure 8).

In the pasture, the OVF generation process was sometimes controlled by infiltration capacity (HOF) and at other times by soil saturation (SOF). To calculate the percentage of each contribution, tension values were converted to antecedent soil moisture contents, and if saturation was attained by adding each net rainstorm depth to the unfilled porosity of the profile, this amount was considered as SOF; if not, the OVF generated when the 15-min rainfall intensity exceeded the near-surface K_{sat} value (4·0 mm/hr) was considered as HOF. For the years 2002 and 2003, about 55% can be accounted as SOF and 40% as HOF. These estimates are approximate, given the inaccuracies of tension measurements, the strongly non-linear form of the moisture-tension relation near saturation, and the fact that the perched water table probably declined a few decimetres below the surface for part of these days, reducing the contribution of the uppermost soil to the effective transmissivity. Table II indicates that conversion of forest to pasture increased OVF from about 5% of throughfall to about 19%.

In most of the events, more SSF was measured in the pasture trough than under the forest trough, although occasionally the reverse was true. Given the generally higher moisture contents and water table elevations at the pasture sites, a larger fraction of the surviving macropores were probably utilized in most storms, but

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when the forest soils were fully wetted, a larger set of macropores, reflected by the outliers (not shown in Figure 6) would be available. The small volumes of SSF in the pasture is in general agreement with the low measured transmissivity; averaged values of K_{sat} in Figure 6(b) indicated a transmissivity somewhat less than 0·1 m^2 d^{-1} above the plinthite, and a back-calculated value from the maximum volumes of SSF in Figure 9(b) (2 mm d^{-1} from a 12-m long slope with a gradient of 0·28) would also be 0·1 m^2 d^{-1}. This estimate was in rough agreement with the value obtained from the regression of K_{sat} against depth [$K_{sat} = 0{\cdot}42 \exp(-6{\cdot}04\ d)$ where d = depth (m); $n = 4$; $r^2 = 0{\cdot}73$], integrated from 0·9 m depth to the soil surface, giving a transmissivity value of about 0·08 m^2 d^{-1}.

Streamflow

A summary of precipitation-discharge relations showed that 3·2% of the net precipitation left the FC as streamflow, and 17·3% left the PC (Table III). The runoff coefficient (runoff volume/rainfall volume) of individual storm responses for the whole catchment ranged from 0 when the soil profile was dry and the rainfall intensity was small to almost 1 when the soil was saturated, generally increasing through the wet season. The storm hydrographs typically lasted for 6–24 h, and had rise times (onset of rainfall to peak) and centroid lags (rainfall centroid to flow centroid) of only a fraction of an hour. This storm runoff was conveyed from the ridge by the first-order channels shown in Figure 1. It is likely that some recharge of the deeper water table occurred through the stream beds that cross the lower slopes of the ridge, but an estimate of this recharge based on the area of a stream bed, the hydraulic conductivity of plinthite, and the duration of storm runoff suggests this loss was small.

To illustrate characteristics of individual flow events, three hydrographs were selected mainly for similarity of rainfall amount and intensity in the two cover types (Figure 10 and Table IV). In all the selected storms, the PC hydrographs had higher runoff coefficients, smaller rise times and centroid lags and the hydrographs were more peaked compared to the FC.

The intensity of storm no. 1 exceeded the median K_{sat} near the surface in the PC (median 4·0 mm h^{-1}) for 68% of the storm (92% of the volume), suggesting that Horton OVF made a significant contribution to the flow generation in the PC. In this case no tension data were available, but the event was at the beginning of the wet season, the antecedent rainfall was not sufficient to produce near-saturated conditions in the whole catchment, even though it probably occurred near the channel producing some SOF and SSF contribution. On the other hand, the high near-surface conductivity of the FC soil and the presence of a shallow impeding layer, were consistent with the delayed response and dominance of SOF and SSF.

Storm no. 2 (Figure 10(b)) with intermediate depth (29–30 mm) and intensity (max 15 min, 19–23 mm h^{-1}) occurred later in the wet season. The intensities in this event exceeded the near-surface K_{sat} in the FC 72% of the time (91% in volume), while the soil was near saturation with an average

Table III. Annual discharge, precipitation and mean ratio flow: precipitation (Q/P)

Year	2000 (mm)	2001 (mm)	2002 (mm)	2003 (mm)	Q/P (%) Mean ratio
Forest					
P_{net}—Net precipitation (throughfall)	1628	1717	1584	1223	
Q—Discharge	41	63	46	43	
Q/P_{net}[a]	2·5	3·7	2·9	3·5	3·2
Pasture					
P—Precipitation	1869	2032	1790	1384	
Q—Discharge	275	272	320	319	
Q/P	14·7	13·4	17·9	23·1	17·3

[a] Net precipitation (throughfall) was employed in the forest.

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Table IV. Characteristics of the three selected hydrographs. Rainfall and runoff time attributes are: time of rise—time difference between the start of a discharge and its peak and discharge peak and centroid lag—time difference between half of the rainfall and half of the discharge event

Event number (date, year)	No. 1 (January 1–2, 2000)		No. 2 (April 27, 2003)		No. 3 (April 27, 2002)	
	Pasture	Forest	Pasture	Forest	Pasture[a]	Forest[a]
Total rainfall (mm)	98	96	29	30	11	11
7-day antecedent rainfall (mm)	145	103	62	55	61	61
Max int. 15 min (mm h^{-1})	80	84	19	23	34	34
Max int. 60 min (mm h^{-1})	58	59	14	14	11	11
Time of rise (min)	45	90	45	255	45	75
Centroid lag (min)	30	91	22	150	20	45
Runoff coefficient (%)	41	29	25	15	19	9

[a] Precipitation for the 2002 wet season was measured only with the forest pluviometer.

tension of −1·2 kPa throughout the whole 90 cm profile. In this case, SOF was likely to have been the dominant process. In the FC the sequential storms produced a slower rise under the more intense part of the storm and a quicker response on the second peak, probably because of the contribution of the delayed SSF and OVF on the saturated areas.

The hydrograph of event no. 3 (Figure 10(c)), again late in the wet season, showed the flow response to a small storm (11 mm) with intermediate intensity (max 15 min, 30–34 mm h^{-1}). In the PC, the soil was near saturation with an average tension of −5 kPa in the whole 90 cm profile, but the small amount of rain was not enough to produce the saturation of the profile, whereas rainfall intensity exceeded the near-surface K_{sat} for 75% of the time (98% of the volume), indicating the dominance of Horton OVF. In the FC, the hydrograph shows a delayed response suggesting again that SSF and OVF on the saturated areas were the most important processes.

Annual water balance

The water balance was employed to calculate the actual evapotranspiration according to the following equation:

$$\mathrm{ET} = \mathrm{P} - \mathrm{Q} - \Delta \mathrm{S}_{0-90} - \mathrm{D} \tag{1}$$

where ET, P, Q, ΔS_{0-90} and D are actual evapotranspiration, precipitation, streamflow, change of water storage at the 0–90 cm soil profile and vertical drainage at 90 cm depth.

Precipitation was considered as total precipitation in both forest and pasture, considering that the interception by leaves was evaporated to the atmosphere. Soil tension measurements from the end of water years 2002 and 2003 suggested that for the whole 90 cm profile yearly changes in water storage (ΔS_{0-90}) could be considered negligible and the water balance equation could be rewritten as ET = P − Q − D. Because the vertical pressure gradients were small, drainage was estimated as the product of unit head gradient and the unsaturated hydraulic conductivity $K(\psi)$ calculated with the Mualem–Van Genuchten model (Van Genuchten *et al.*, 1991). This simplified approach was employed as only daily measurements of ψ were performed in the present study. Calculated values of average annual D at the 90 cm depth in the pasture were 51 mm in 2002 (0·3–118 mm) and 27 mm in 2003 (0·1–63 mm). In the forest the average D was 115 mm in 2002 (7–486 mm) and 25 mm in 2003 (0·1–105 mm), where values in parenthesis are minimum and maximum tension at 90 cm depth.

The components of the annual water balance are summarized in Table V. For 2002 and 2003, ET was estimated for the forest as 4·5 and 3·6 mm d^{-1}, respectively, and for the pasture 3·9 and 2·8 mm d^{-1},

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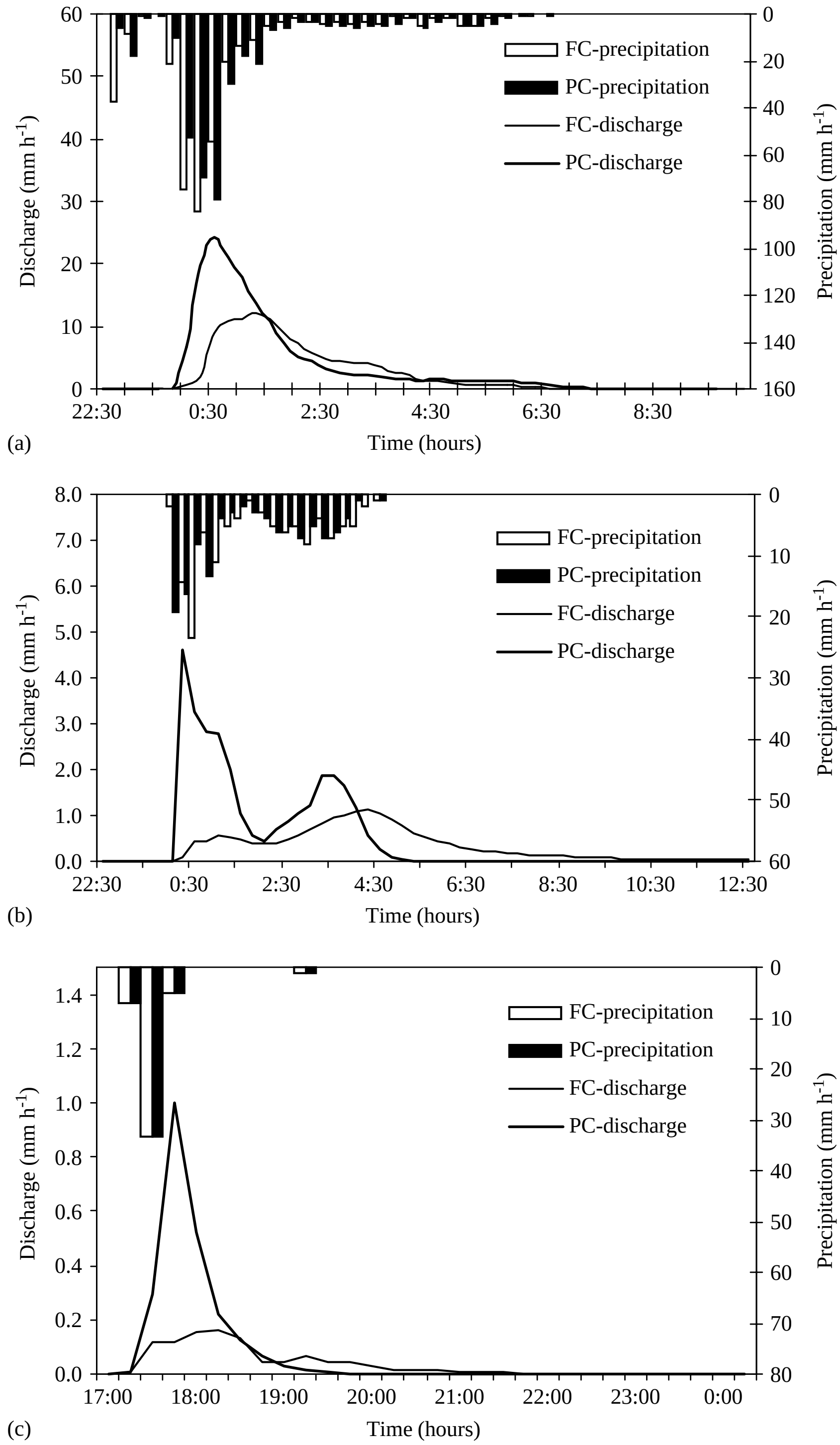

Figure 10. Total precipitation and discharge hydrographs for the pasture and forest catchments: (a) January 1–2, 2000, (b) April 27, 2003, and (c) April 27, 2002

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Table V. Annual water balance[a] components for Fazenda Vitória: mean values of precipitation and discharge. Actual ET estimated from water balance

Year	2002	2003
Precipitation (mm year^{-1})	1790	1384
Forest		
Discharge (mm year^{-1})	46	43
Drainage (mm year^{-1})	115	25
Actual ET (mm year^{-1})	1629	1316
Actual ET (mm day^{-1})	4·5	3·6
Pasture		
Discharge (mm year^{-1})	320	319
Drainage (mm year^{-1})	51	27
Actual ET (mm year^{-1})	1419	1038
Actual ET (mm day^{-1})	3·9	2·8

[a] Hydrological year (from October of the preceding year to September of referenced year).

respectively. These estimated values of ET agreed with the results of Jipp *et al*. (1998) using Time Domain Reflectometer (TDR) measurements (0–8 m depth) on the plateau of the same site from 1991 to 1994. These authors estimated ET in two dry years, 1992 (1022 mm of rainfall) and 1993 (1424 mm of rainfall), ET in the forest as 3·1 and 4·2 mm d^{-1}, respectively, and in the pasture ET as 2·6 and 3·7 mm d^{-1}, respectively. The remaining analysed years, 1991 (2154 mm of rainfall) and 1994 (2099 mm of rainfall), ET in the forest was 5·0 and 4·4 mm d^{-1}, respectively, and in the pasture 4·2 and 4·7 mm d^{-1}. Our estimate was also close to the study performed in eastern Amazon by Hölscher *et al*. (1997) where the average ET was calculated as 3·9 mm d^{-1} from a young secondary forest, and to the study of Shuttleworth (1988), where the average ET was calculated as 3·6 mm d^{-1} over a primary forest in central Amazonia.

The estimated ET values in the present study were of the same magnitude as other published values for Amazonia, though they were on the higher side of the published range. There are several potential reasons for such a bias. One is a possible underestimation of the drainage term, because the daily tension measurements may have missed short-term variations. Sparse roots beneath the plinthite in the forest may have increased macropore drainage during the wet season, but these same sparse roots would also drive evapotranspiration below the depth of our tension measurements, offsetting the underestimation of ET later in the dry season. We were not able to quantify these offsetting effects from our measurements, but our estimates of ET were close to those of Jipp *et al*. (1998) when controlled for annual precipitation.

CONCLUSIONS

Plinthic soils in Eastern Amazonia generated frequent and extensive SOF, even under forest, because the soils had a strong vertical gradient of K_{sat}, which declined to extremely low values at the plinthite layer. These characteristics limited both vertical drainage and lateral sub-surface flow, and kept the soil water contents close to saturation throughout most of the wet season, when rainstorms are frequent. However, in the forest, SOF from small hillslope plots accounted for only ∼4% of annual precipitation, and the annual quickflow in the first-order stream was only 3·2% of rainfall. The calculated drainage through the plinthite in the forest was very variable, ranging from few mm year^{-1} of water (7 mm year^{-1} in 2002 and 2 mm year^{-1} in 2003) where the plinthite was indurated to hundreds of mm year^{-1} (486 mm year^{-1} in 2002 and 105 mm year^{-1} in 2003) where the plinthite was soft and friable. The mean actual evapotranspiration calculated for the forest was therefore 1629 and 1316 mm for 2002 and 2003 (including evaporation of 206 and 161 mm, respectively, of intercepted water).

Replacement of the forest with pasture for 30 years caused a reduction of macropores and a decrease in saturated hydraulic conductivity to values that promoted larger volumes (19% of annual rainfall) of both HOF (∼40%) and SOF (∼60%) from hillslope plots. Quickflow from the PC was 17% of annual rainfall. Soil moisture values remained generally higher than those in the FC, promoting frequent saturation. Drainage through the indurated plinthite beneath this catchment was 51 and 27 mm $year^{-1}$ for 2002 and 2003, respectively, and the actual evapotranspiration was calculated by residual as 1419 and 1038 mm $year^{-1}$ for 2002 and 2003, respectively, plus a small but unknown amount of intercepted water. These results and the soil characteristics measured in *capoeira* that has been regenerating for 12 years (Figure 6(c)) suggested that full recovery of the pre-clearing hydrology is likely to require many decades.

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REFERENCES

Biggs TW, Dunne T, Martinelli LA. 2004. Natural controls and human impacts on stream nutrients concentrations in a deforested region of the Brazilian Amazon basin. *Biogeochemistry* **68**: 227–257.

Biggs TW, Dunne T, Domingues TF, Martinelli LA. 2002. Relative influence of natural watershed properties and human disturbance on stream solute concentrations in the southwestern Brazilian Amazon basin. *Water Resources Research* **38**: 1150. DOI:10·1029/2001WR000271.

Bonell M, Balek J. 1993. Recent scientific developments and research needs in hydrological processes of the humid tropics. In *Hydrology and Water Management in the Humid Tropics. Hydrological Research and Strategies for Water Management*, Bonell M, Hufschmidt MM, Gladwell JS (eds). Cambridge University Press: Unesco; 167–260.

Clapperton C. 1993. In *Quaternary Geology and Geomorphology of South America*. Elsevier: Amsterdam; 779.

Dunne T. 1978. Field studies of hillslope flow processes. In *Hillslope Hydrology*, Kirkby MJ (ed). John Wiley & Sons: Chichester; 227–293.

Elsenbeer H. 2001. Hydrologic flowpaths in tropical rainforest soilscapes-a review. *Hydrological Processes* **15**: 1751–1759. DOI: 10·1002/hyp·237.

Elsenbeer H, Lack A. 1996. Hydrological pathways and water chemistry in Amazonian rain forests. In *Advances in Hillslope Processes*, Anderson MG, Brooks SM (eds). Wiley: Chichester; 939–958.

Elsenbeer H, Newton BE, Dunne T, Moraes JM. 1999. Hydraulic conductivities of Latosols under pasture, forest and teak in Rondônia, Brazil. *Hydrological Processes* **13**: 1417–1422.

Franken W, Leopoldo PR. 1986/1987. Relações entre fluxos de água subterranea e superficial em bacia hidrográfica caracterizada por cobertura florestal Amazônica. *Acta Amazonica* **16/17**: 253–262. (in Portuguese with summary in English).

Franken W, Leopoldo PR, Matsui E, Ribeiro MNG. 1992. Estudo da interceptação da água de chuva em cobertura florestal amazônica do tipo terra firme. *Acta Amazonica* **12**: 327–331. (in Portuguese with summary in English).

Gash JHC, Nobre CA, Roberts JM, Victoria RL. 1996. An overview of ABRACOS. In *Amazonian Deforestation and Climate*, Gash JHC, Nobre CA, Roberts JM, Victoria RL (eds). Wiley: Chichester; 1–14.

Hodnett MG, Pimentel de Silva L, da Rocha HR, Cruz Senna R. 1995. Seasonal soil water storage changes beneath central Amazonian rainforest and pasture. *Journal of Hydrology* **170**: 233–254.

Hodnett MG, Oyama MD, Tomasella J, Marques Filho O. 1996. Comparisons of long-term soil water storage behaviour under pasture and forest in three areas of Amazonia. In *Amazonian Deforestation and Climate*, Gash JHC, Nobre CA, Roberts JM, Victoria RL (eds). Wiley: Chichester; 57–77.

Hölscher D, Sá TDA, Bastos TX, Denich M, Fölster H. 1997. Evaporation from young secondary vegetation in eastern Amazonia. *Journal of Hydrology* **193**: 293–305.

INPE. 2000. *In Monitoring of the Brazilian Amazonian Forest by Satelite, 1998–1999*. Instituto de Pesquisas Espaciais: São José dos Campos; 22.

Jipp PH, Nepstad DC, Cassel DK, Reis de Carvalho C. 1998. Deep soil moisture storage and transpiration in forests and pastures of seasonally-dry Amazonia. *Climatic Change* **39**: 395–412.

Leopoldo PR. 2000. Ciclo hidrológico em bacias experimentais na Amazônia Central. In *Amazônia: Um ecossistema em Transformação*, Salati E, Absy ML, Victória RL (eds). Inpa & CNPq: Manaus; 87–117. In (in Portuguese).

Lesack LFW. 1993. Water balance and hydrologic characteristics of a rain forest catchment in the central Amazon basin. *Water Resources Research* **29**: 759–773.

Lloyd CR. 1990. The temporal distribution of Amazonian rainfall and its implications for forest interception. *Quarterly Journal of the Royal Meteorological Society* **116**: 1487–1494.
Lloyd CR, Marques AO. 1988. Spatial variability of throughfall measurements in Amazonian rainforest. *Agriculture and Forest Meteorology* **42**: 63–73.
Luxmoore RJ. 1981. Micro, meso, and macroporosity. *Soil Science Society of America Journal* **45**: 671–672.
Neill C, Deegan LA, Thomas SM, Cerri CC. 2001. Deforestation for pasture alters nitrogen and phosphorus in small Amazonian Streams. *Ecological Applications* **11**: 1817–1828.
Nepstad DC, Uhl C, Serrão EAS. 1991. Recuperation of a degraded Amazonian landscape: forest recovery and agricultural restoration. *Ambio* **20**: 248–255.
Nepstad DC, Veríssimo A, Alencar A, Nobre C, Lima E, Lefebvre P, Schlesinger P, Potter C, Moutinho P, Mendoza E, Cochnrane M, Brooks V. 1999. Large-Scale impoverishment of Amazonian forests by logging and fire. *Nature* **398**: 505–508.
Nortcliff S, Thornes JB. 1989. Variations in soil nutrients in relation to soil moisture status in a tropical forested ecosystem. In *Mineral Nutrients in Tropical Forest and Savanna Ecosystems*, Proctor J (ed). Blackwell: Oxford; 43–54.
Nortcliff S, Thornes JB, Waylen MJ. 1979. Tropical forest systems: a hydrological approach. *Amazonianamazoniana* **4**: 557–568.
Nortcliff S, Ross SM, Thornes JB. 1990. Soil moisture, runoff and Sediment yield from differentially cleared tropical rainforest plots. In *Vegetation and Erosion*, Thornes JB (ed). John Wiley & Sons: Chichester; 419–436.
Ross SM, Thornes JB, Nortcliff S. 1990. Soil hydrology, nutrient and erosional response to the clearance of terra firme forest, Maracá Island, Roraima, Northern Brazil. *The Geographical Journal* **156**: 267–282.
Shuttleworth WJ. 1988. Evaporation from Amazonian rainforest. *Proceedings of the Royal Society of London* **B.233**: 321–346.
Soil Survey Staff. 1988. *Keys to Soil Taxonomy*, SMSS Technical Monograph No. 6. U.S. Department of Agriculture, Cornell University: Ithaca; 280.
Sombroek WG. 1966. *In Amazon Soils, a Reconnaissance of the Soils of the Brazilian Amazon Region*. Centre for Agricultural Publications and Documentations: Wageningen; 292.
Sombroek WG. 1984. Soils of the Amazon region. In *Amazon Limnology and Landscape Ecology of a Mighty Tropical River and its Basin*, Sioli H (ed). Dr W. Junk Publishers: Dordrecht; The Netherlands; 521–535.
Tomasella J, Hodnett MG. 1996. Soil hydraulic properties and van Genuchten parameters for an oxisol under pasture in central Amazonia. In *Amazonian Deforestation and Climate*, Gash JHC, Nobre CA, Roberts JM, Victoria RL (eds). Wiley: Chichester; 101–123.
Ubarana VN. 1996. Observations and modeling of rainfall interception at two experimental sites in Amazonia. In *Amazonian Deforestation and Climate*, Gash JHC, Nobre CA, Roberts JM, Victoria RL (eds). Wiley: Chichester; 151–161.
Van Genuchten MTh, Leij FJ, Yates SR. 1991. *The RETC code for quantifying the hydraulic functions of unsaturated soils*, EPA/600/2-91-065, Robert S. Kerr Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Ada, Oklahoma; 93.
Williams MR, Melack JM. 1997. Solute export from forested and partially deforested catchments in the central Amazon. *Biogeochemistry* **38**: 67–102.
Williams MR, Fisher TR, Melack JM. 1997. Solute dynamics water and groundwater in a central Amazon catchment undergoing deforestation. *Biogeochemistry* **38**: 303–335.
Wright IR, Gash JHC, da Rocha HR, Roberts JM. 1996. Modelling surface conductance for Amazonian pasture and forest. In *Amazonian Deforestation and Climate*, Gash JHC, Nobre CA, Roberts JM, Victoria RL (eds) Wiley: Chichester; 437–458.

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