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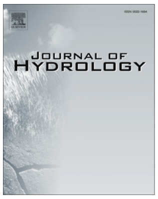

Land-use change in the Atlantic rainforest region: Consequences for the hydrology of small catchments

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SUMMARY

The Atlantic forest of Brazil is one of the most endangered ecosystems in the world. Despite approximately 500 years of intense land-use change in this biome, the influence of land-use changes on hydrological processes have yet to be investigated in-depth. To bridge this gap, we studied various features of three small catchments covered by pristine original montane cloud forest, pasture, and eucalyptus for 2 years (January 2008–December 2009), including the hydraulic properties of soils, throughfall, overland flow and streamflow processes. The forest saturated hydraulic conductivity (K_{sat}) was higher near the soil surface (0.15 m depth) compared to eucalyptus and pasture. As a consequence, higher overland flow generation in terms of volume was observed in pasture and eucalyptus. Despite this increase in overland flow generation, overland flow coefficients (overland flow: precipitation ratio) were substantially low throughout the study period with slightly higher values in 2009. These low overland flow coefficients were attributed to the large predominance of low rainfall intensities ($<10\ \mathrm{mm\ h^{-1}}$) as well as high K_{sat} spatial variability. These overland flow results and the absence of perched water table showed that catchments seem still to be dominated by vertical flowpaths irrespective of land-use. In this sense, the annual streamflow is still dominated by baseflow in all of the catchments. Therefore, despite reductions regarding interception and saturated hydraulic conductivity when converting forest to eucalyptus and pasture, the prevailing rainfall intensities do not cause runoff generation processes to be substantially different among land-uses. Forest and eucalyptus convert a similar proportion of annual precipitation to annual streamflow, with the more likely factors for these results being the high interception under forest and high transpiration under eucalyptus. Finally, cloud forest conversion to pasture does not promote significant monthly streamflow change.

1. Introduction

The Atlantic forest (*Mata Atlântica*) which extends mainly along Brazil's Atlantic coast is one of the most important forested biomes of Brazil (Morellato and Haddad, 2000). According to Ribeiro et al. (2009), of the 1.4 million km^2 of the original forest distribution, only about 163.775 km^2 remain in 2005 (12% of the original area). These remaining areas are often distributed in small and degraded fragments inserted into a matrix altered by human activity (Lira et al., 2012). The severity of disturbance is alarming mainly because the Atlantic forest is an ancient tropical rainforest, a biodiversity hotspot, and an endemism center of several species (Myers et al. 2000; Murray-Smith et al., 2009).

The *Serra do Mar* is a series of mountains running parallel to the coast mainly in the States of São Paulo and Rio de Janeiro. This region is generally covered by the most well preserved Atlantic forests remnants generally described as "dense tropical rain forest." However, this "rain forest" is actually a diverse ecosystem encompassing different types of forests that are classified according to the altitude along the scarps, including areas of coastal flooded forest (sandy coastal plain vegetation also called *restinga*) at sea level, lowland, sub-montane and montane forests (Veloso et al., 1991; Morellato and Haddad, 2000; Scarano, 2002).

Montane tropical cloud forests (MCFs) are members in the montane forest group, being defined as the montane forests that are frequently exposed to clouds at the canopy level. They occupy a

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special niche in tropical forest ecology due to peculiar characteristics (Bruijnzeel et al., 2011). Several biodiversity hotspots described by Myers et al. (2000) include MCFs, because these forests are considered areas of high endemism of several species (Aldrich et al., 1997). One of these places where MCFs occur is the Atlantic forest region in southeast Brazil (Bruijnzeel et al., 2011).

In terms of hydrology, MCFs are peculiar since they may have additional water input through cloud-water interception that is less common in lowland areas (Bruijnzeel, 2006; Bruijnzeel et al., 2011). MCFs canopy evaporation is generally lower than lowland forests because the former are subjected to lower temperatures and thus they remain wet for longer periods since they are frequently subjected to clouds at the canopy level (Giambelluca et al., 2011).

Maintaining MCFs is also critical in light of climate change (Ponette-González et al., 2009; Bruijnzeel et al., 2011). As these forests depend on low clouds and fog water input (Bruijnzeel, 2006), any change in the height or frequency in which these clouds come into contact with the forest may disrupt their natural water dynamics (Ray et al., 2006), and consequently the distribution of several species (Pounds et al., 1999). In this respect, land-use change for example from forest to pasture may lead to such changes in water dynamics (Bruijnzeel et al., 2011).

Considering the importance of the Atlantic forest as cloud forest and biodiversity hotspot, little information is available on its basic functioning especially regarding hydrological aspects (Coelho Neto, 1987; Fujieda et al., 1997; Anido, 2002; Ranzini and Lima, 2002; Ranzini et al., 2004a, 2004b; Arcova et al., 2003). More importantly, the influence of land-use changes on hydrological processes has yet to be investigated in-depth. Between the coastal Atlantic forest and the beginning of the Atlantic plateau, a series of land-use changes have been observed, and areas previously occupied by ancient MCF are currently occupied by low productivity pastures and eucalyptus industrial plantations.

Water flow in soils is mainly governed by soil physical properties and also by some chemical characteristics. Land-use change may alter the structure, bulk density (Braimoh and Vlek, 2004), pore-size distribution (Wairiu and Lal, 2006), carbon content (Neill et al., 1997), and soil biological activity (e.g. earthworm abundance) (Bormann and Klaassen, 2008) influencing the water movement in the soil-plant-atmosphere continuum. Additionally, when forest conversion occurs in a region dominated by rainforests, the replacement of deep-rooted native forest by shallow-rooted pasture can disturb the hydrological cycle in many ways (Gash et al., 1996). One of the most important changes due to forest conversion in lowland tropical forests is the increase in streamflow (Bruijnzeel, 2004, see Fig. 2). This is caused by a combination of lower evapotranspiration rates of crops than old mature tropical forests, with a decrease in soil infiltration due to the increase in soil bulk density in the crop field (Bruijnzeel, 2004). On the other hand, in the 1980s, it was hypothesized that the conversion of MCF would lead to a decrease in streamflow instead of an increase as observed in lowland tropical forests. This decrease may occur because the subsequent crop would not have the capacity to intercept clouds like the forest, hence resulting in decreasing water input to catchments coupled with low evaporation rates of MCF (Zadroga, 1981; cited by Bruijnzeel et al. (2011)). There are still few studies investigating water yield in MCF to test Zadroga's hypothesis (Bruijnzeel, 2006; Ponette-González et al., 2009). Therefore, studies addressing these issues are urgently needed because MCFs are disappearing at an elevated rate (Ponette-González et al., 2009).

In order to understand the hydrological dynamics of the Atlantic forest and to evaluate possible land cover transformation effects on it, we investigated the water pathways in three small catchments covered by pristine MCF, pasture, and eucalyptus located in the northern portion of the *Serra do Mar* in the State of São Paulo (southeastern region of Brazil). For two consecutive years (2008–2009), the following hydrological variables were monitored: precipitation, throughfall, overland flow, soil saturated hydraulic conductivity, and streamflow.

2. Materials and methods

2.1. Study area

The study was carried out in an area between São Luiz do Paraitinga and Ubatuba municipalities, São Paulo State, Brazil. These cities are located about 200 km the megalopolis of São Paulo. Three small catchments with different land-uses, i.e., forest (area 11.5 ha, mean slope of 28 ± 14%), pasture (4.7 ha, mean slope of 37 ± 25%) and eucalyptus (area 35.5 ha, mean slope of 30 ± 17%) were selected. The mean slope followed by standard deviation indicates a wide variety of slopes, which is typical for this region. These measurements were obtained from a 5-m-resolution digital-elevation model. All studied areas are located in the State of São Paulo on the border between the Atlantic plateau and the scarps of a mountain chain called the *Serra do Mar*, which borders and spans the Atlantic Ocean coastline and separates the coast from the interior plateau lands. The forest catchment was located inside the State Park of *Serra do Mar* in the Santa Virginia unit in the crest of the mountain chain (23°17′–23°24′S, 45°03′–45°11′W), while the pasture and eucalyptus catchments were located on adjacent areas on the Atlantic Plateau (Fig. 1). The distance between the eucalyptus and pasture catchments from the forest catchment was 8.5 km and 18 km, respectively. This distance was imposed by the State Park area limits and similar soil types.

Geologically, this region is characterized by dissected landscapes with crystalline rocks composed mainly of granites, gneisses, and migmatites (Furian et al., 1999). Based on a soil field survey in all of the catchments, the soils are young and classified mainly as entisols and inceptisols (Udepts), with the latter predominating. All of these soils formed from gneisses. A more complete description of some soil features can be seen in Table 1. Additionally, all soils present ochric epipedon and blocky structure within A and B-horizons. Regarding block size, the soil blocks increase in size toward lower depths in the soil profile. Due to strong variation in topography, soil depth is also variable and may reach 1.5–2 m. However, the regolith (this also includes C horizon) may be far deeper.

The local climate is temperate tropical, and based on 20-year (from 1973 to 2004) weather station data available in the Santa Virgínia management unit of the State Park of *Serra do Mar*, we calculated a mean annual precipitation of 2180 ± 465 mm and mean annual temperature of 21 ± 1.2 °C. The rainy season occurs from October to March with the maximum rainfall in November–February and minimum in June–August (Tabarelli and Mantovani, 1999). Beyond the influence of equatorial and tropical air masses, this precipitation is strongly influenced by orographic effects, which combined with the complex mountainous topography of the *Serra do Mar*, produces large spatial variability in mean annual rainfall in different locations. This region is frequently covered in fog beginning late in the afternoon and frequently persisting throughout part of the morning. Fog is more common during the dry season, but it is observed sporadically all year long.

The Santa Virgínia unit has an area of 5000 ha with altitude varying from 850 to 1100 m. The forest is classified as Dense Montane Rainforest according to the Brazilian classification (Veloso et al., 1991). Aboveground biomass of a nearby study area was estimated as 280 t ha^{-1} and the canopy had an average height of 15 m with some emergent trees reaching 30 m (Alves et al., 2010). The

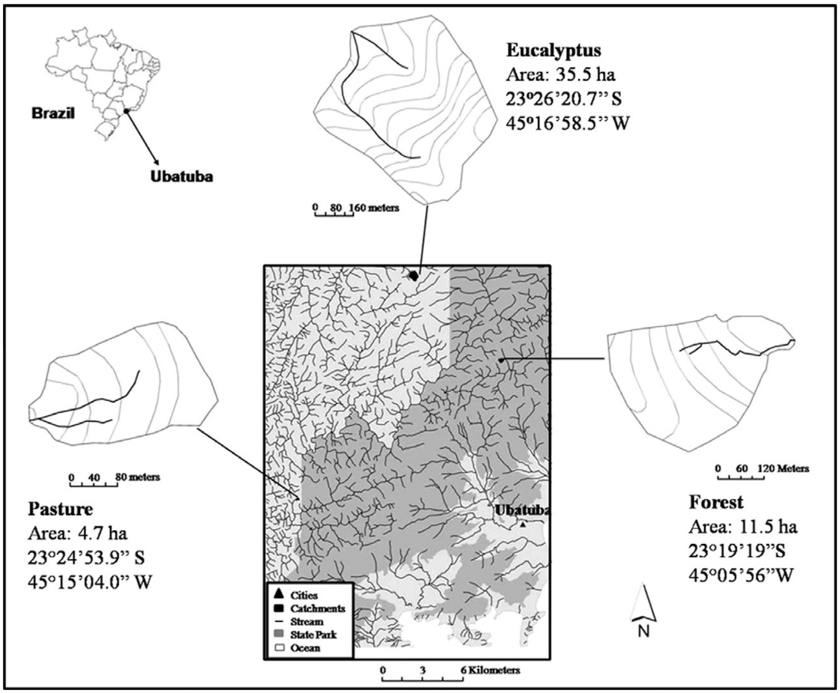

Fig. 1. State Park of Serra do Mar – Santa Virginia unit. Pasture and eucalyptus catchments were located outside of the park on adjacent areas. The contour lines of the topographic map represents 20 m interval.

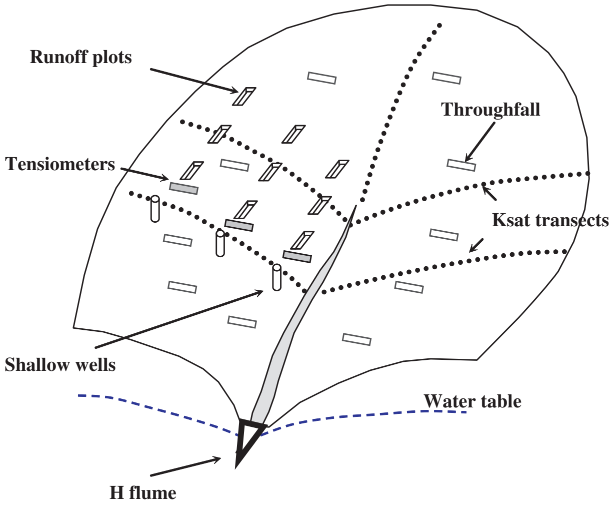

Fig. 2. Schematic of experimental setup installed in all catchments.

forest presents a two- to three-layer canopy and it also presents a very dense bamboo understorey. Tree density (⩾4.8 cm diameter at breast height) was estimated as 1230 individual trees per hectare (Alves et al., 2010). Tree branches are frequently covered by epiphytes and moss all year long. No clear visual evidence of reduction of leaf area index could be reported in this study area during the years of study. Based on all these features, the forest may be classified as a "lower montane cloud forest" (*sensu* Bruijnzeel et al., 2011).

At the eucalyptus site, the catchment was previously used for pasture established in the early 1960s after forest clearing. Heavy machinery was used for such land-use conversion. Since 2004, a logging firm (Votorantim Celulose e Papel – VCP) converted the pasture into a eucalyptus plantation (*Eucalyptus urograndis*). The trees were spaced 3 × 2 m, and the age of this plantation was 4 years in 2008, and trees were on average 11 m tall. Tree density was about 1650 individuals per hectare. In conditions similar to our study site, eucalyptus, at the age of 4, may present rooting depth down to 2.5 m (Almeida and Soares, 2003). In this catchment, plantation trees occupied 65% of the 35.5 ha basin, with

Table 1
Description of some soil characteristics.

Land-use	Depth (m)	Organic carbon content (g dm^{-3})	Bulk density (Mg m^{-3})	Clay (%)	Sand (%)
Forest	0.00–0.15	68.0 ± 9.5	0.95 ± 0.1	21.3 ± 2.5	51.4 ± 6.8
	0.15–0.30	48.7 ± 7.2	1.19 ± 0.1	25.4 ± 3.8	50.0 ± 4.0
	0.30–0.50	32.7 ± 8.1	1.27 ± 0.1	27.1 ± 1.4	52.7 ± 3.8
	0.50–0.90	16.3 ± 5.1	1.44 ± 0.1	25.4 ± 1.4	60.2 ± 2.1
Eucalyptus	0.00–0.15	46.7 ± 14.0	1.38 ± 0.1	31.7 ± 1.4	55.3 ± 5.3
	0.15–0.30	40.3 ± 11.4	1.38 ± 0.1	35.8 ± 1.4	50.7 ± 2.5
	0.30–0.50	23.3 ± 7.5	1.32 ± 0.1	37.5 ± 4.3	52.7 ± 2.8
	0.50–0.90	18.3 ± 6.4	1.37 ± 0.1	41.7 ± 1.4	60.2 ± 2.1
Pastore	0.00–0.15	43.3 ± 4.6	1.33 ± 0.1	23.8 ± 2.2	58.4 ± 2.1
	0.15–0.30	23.3 ± 1.5	1.58 ± 0.1	25.4 ± 2.6	56.9 ± 3.3
	0.30–0.50	17.0 ± 1.0	1.57 ± 0.1	28.8 ± 3.3	53.4 ± 3.6
	0.50–0.90	14.7 ± 1.5	1.47 ± 0.1	31.7 ± 5.9	52.3 ± 2.0

35% native remnants located in the riparian area covered by an abandoned pasture with secondary growth. Following forest plantation and fertilization, heavy machinery was used only for harvesting. Similar to our forest site, visually speaking, eucalyptus seems not to show any variation of leaf canopy even during the driest months.

The pasture catchment was converted into an orange and lemon orchard in 1963. It remained under this land-use until 1968 when it was converted to the current exotic grass (*Brachiaria decumbens* Stapf). Heavy machinery was used only for land-use conversion. Various native species of trees, herbs, and shrubs compete with *B. decumbens* Stapf in the area. From the cattle husbandry viewpoint, *Psidium guajava*, *Psidium cattleianum*, and *Pteridium sp*. are only a small sample from an abundant presence of undesirable species in the study area. The stocking density varies from 2 to 3 heads ha^{-1} during the year, which keeps grass height low, being close to the ground most of time. Numerous narrow cattle trails occur along the contour lines; however, only a few of them connect directly to the stream channel. In addition, pasture streams present high levels of sediment deposition. Consequently, there is a poorly defined fluvial channel surrounded by wetland plants (e.g., *Typha* sp.) that develop under an aquept.

2.2. Experimental design

The study was initiated in January 2008 and continued up to December 2009. During this period, gross precipitation was measured continuously as 10-min rainfall totals with tipping-bucket rain gauges with a resolution of 0.254 mm (RainLog, RainWise Inc.) and manually by three trough-type collectors, all installed in cleared areas adjacent to each catchment. In order to qualify as a rainfall event, at least 0.5 mm of rainfall must have been recorded in half an hour. Events were demarcated by at least 2 h without rain (Germer et al., 2006).

Ten fixed trough-type collectors were installed and randomly positioned below the forest and eucalyptus canopies to estimate net precipitation as throughfall (Fig. 2). The trough-type collectors were constructed from 100-mm-diameter PVC pipes, which were connected via flexible tubes to 20 L plastic canisters. These collectors were installed horizontally 1.5 m aboveground. The collecting area was 0.15 m^2 per collector. Throughfall was measured on a weekly basis in 2008, and due to logistical restrictions, it was measured biweekly in 2009. After each field campaign, the collectors were emptied and cleaned to prevent clogging by debris. In the pasture, interception was not measured but it was estimated based on the work of Coutorier and Ripley (1973).

In all catchment areas, overland flow (OVF) was measured in nine 2.25 m^2 plots. A set of three plots was installed in three locations on the hillslope: downslope, middleslope, and upslope (Fig. 2). Plots were defined by 1.5 m wood frames carefully inserted in the soil in order to avoid disturbance. For plot installation, three similar hillslopes regarding slope and extension were selected in all of the catchments. Downslope, middleslope, and upslope plots were located 15, 40, and 100 m relative to the stream. The overland flow generated in these plots was collected by an open 100-mm-PVC pipes placed horizontally on the soil surface following the scheme described in Moraes et al. (2006). They were monitored weekly in 2008 and biweekly in 2009. Following these sampling intervals, overland flow coefficients were calculated on a weekly basis in 2008 and biweekly basis in 2009 by dividing the amount of overland flow (mm) by the amount of rainfall (mm).

Linear transects of saturated hydraulic conductivity (K_{sat}) were measured from interfluve-to-channel in each catchment (Fig. 2) using a compact constant head permeameter (Amoozemeter Permeameter, Amoozegar, 1992) over depth increments of 0.03–0.15, 0.12–0.30, 0.32–0.50, and 0.72–0.90 m. For each catchment, K_{sat} was measured at 25 points at each depth. Soil cores of 100 cm^3 were collected at 0–15; 15–30, 30–50 cm and 50–90 cm in each catchment to determine soil bulk density and water retention curves.

A set of three 0.5-m-shallow wells was used in the forest and eucalyptus and 0.3-m wells were used in pasture for field verification of perched water table formation. Wells were monitored once a week in 2008 and twice a week in 2009.

Streamflow was measured with an H-flume anchored to the base rock in the case of forest and pasture catchments (Trutrack WT 2000). The water stage was recorded every 5 min with a water-level recorder. For the eucalyptus areas, because the environmental regulatory agency did not permit flume installation, the discharge was estimated by creating a rating curve using the same time step and water-level recorder of the other catchments. The average flow velocity was measured using a flow probe (FP201 "Flow Probe", Global Water). Discharge measurements were done once a week throughout the study period. In cases in which the stage exceeded the highest stage recorded during the manual discharge measurements, the peak discharge was estimated based on marks left by the streamflood on the stream bank walls and then calculating the section area. For calculating streamflow, the highest measured flow velocity was assumed to represent flow velocities during the flood. This estimation was made only twice throughout the study period.

A simplified water balance was employed to calculate actual evapotranspiration of each catchment according to the following equation:

$$\text{ET} = P - Q - \Delta S \tag{1}$$

in which ET is the actual evapotranspiration (mm), P represents the precipitation (mm), Q the total discharge (mm) and ΔS (mm) the change in water storage. The ΔS was assumed to be negligible due to the fact that soil water matric potential in the onset of the period of our records was similar to those at the end of the same period.

In order to determine stormflow contribution to annual streamflow generation, we separated stormflow from baseflow. In doing so, we used the straight-line method (Chow et al., 1988), which consists of dividing the baseflow and stormflow of the storm hydrograph by simply drawing a straight-line on the previous discharge (baseflow) just before any increase in it during a rainfall event until the point of inflexion of the recession limb. This inflexion point was obtained by applying a logarithm to each recession limb. In this paper, we used the term stormflow to denote event flow and baseflow to denote flow that cannot be associated with a specific event (Blume et al., 2007).

2.3. Data analysis

In order to understand the K_{sat} differences among various soil depths (0.15, 0.30, 0.50 and 0.90 m depths) within each land-use and K_{sat} differences among land-uses, the non-parametric Kruskal–Wallis rank sum test was used. If significant differences were found, the non-parametric Mann–Whitney *U*-test was used to identify which group or groups were significantly different. These non-parametric tests were applied since the raw data did not present normal distribution and homocedasticity (using a Shapiro-Wilk test and Box–Cox transformations, respectively). As K_{sat} did not present normal distribution, the median was used as the measure of central tendency.

For comparisons of streamflow and overland flow among land-uses, we first tested the data normality and homocedasticity of these variables. As they did not follow a normal distribution or homogeneity of variance, they were transformed using Box–Cox transformations. We tested the effect of the land-use changes on hydrological variables using the analysis of covariance (ANCOVA) since the precipitation levels varied among the catchments. In doing so, land-use was considered a fixed factor and the monthly precipitation was used as the independent variable (covariate) and mean monthly measurements of the aforementioned variables as the dependent variables. Tukey's Honest Test for unbalanced data (HSD) was then used to explain significant differences detected by the ANCOVA.

All statistical analyses were performed using the software STATISTICA, version 9 for Windows (StatSoft, Inc. 2009). Differences at the $p < 0.05$ level were reported as significant.

3. Results

3.1. Precipitation

A high inter-annual and inter-site annual rainfall variability was observed even in catchments located only a few kilometers apart (Table 2). Compared to 2008, the annual rainfall in 2009 was 70%, 45%, and 50% higher in forest, eucalyptus and pasture, respectively. There was also a marked seasonal variation in the three catchments, with approximately 70% of the total annual precipitation occurring in the summer period (October to March).

The rainfall intensity class of 0–10 mm h^{-1} comprised approximately 85% of the frequency of events (Figs. 3a and 4a) and approximately 70% contribution to the total rainfall for 2008 and roughly 55–60% in 2009 (Figs. 3b and 4b). High intensity rainfall contributed more in 2009 than in 2008 (Figs. 3b and 4b). The frequency distribution of rainfall intensities was similar in 2008 and 2009 (Figs. 3a and 4a), despite differences in total annual rainfall in the three catchments.

3.2. Throughfall and interception

In absolute terms, throughfall under all land-uses varied substantially from 2008 to 2009 reflecting the differences in rainfall levels between these years (Table 2). However, if throughfall is expressed as a fraction of rainfall, the throughfall in the forest catchment averaged approximately 67% of gross annual rainfall for 2008 and 2009. In the case of the Eucalyptus, throughfall was equal to approximately 80% in 2008 and 2009. Though pasture interception was not measured, to avoid neglecting this process we assumed the lower range (14%) of the estimates made by Coutorier and Ripley (1973) could represent our pasture interception (Table 2).

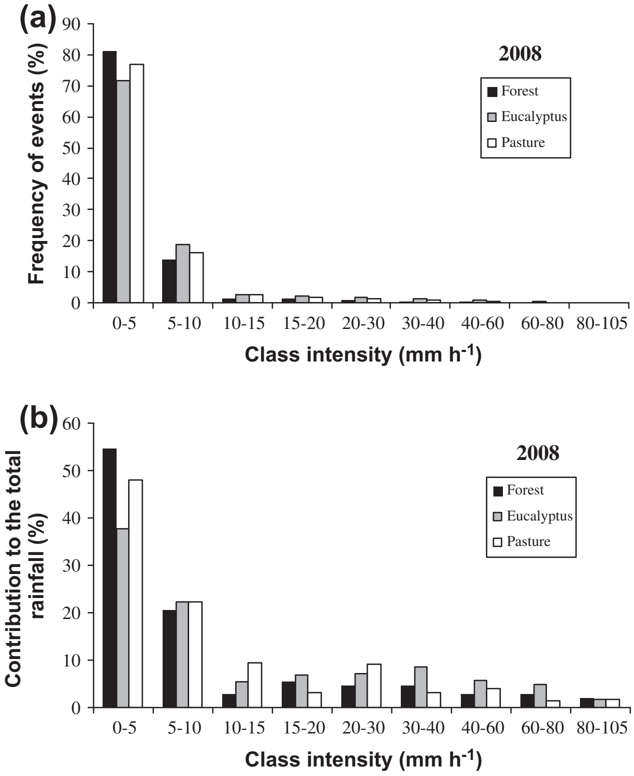

Fig. 3. Frequency distribution of 10-min rainfall intensity (a) and percentage contribution to total rainfall for 2008 (b).

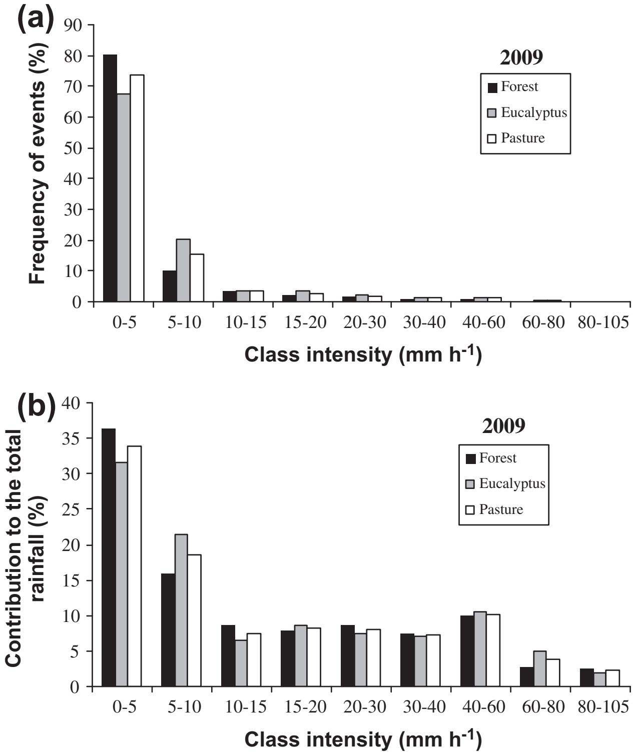

Fig. 4. Frequency distribution of 10-min rainfall intensity (a) and percentage contribution to total rainfall for 2009 (b).

Table 2
Annual sums and ratios of water fluxes for 2008 and 2009 in forest, eucalyptus, and pasture catchments.

	Forest		Eucalyptus		Pasture	
Variable	2008	2009	2008	2009	2008	2009
P (mm)	1717	3003	1290	1885	1430	2120
I (mm)	567	961	246	377	200	297
T (mm)	1150	2042	1044	1508	1230	1823
OV:P	0.005	0.007	0.011	0.021	0.017	0.026
OV:T	0.007	0.009	0.013	0.025	0.029	0.031
Q (mm)	681	1433	496	875	736	1283
BF (mm)	518	1089	432	761	611	718
BF:P	0.31	0.37	0.33	0.40	0.42	0.33
SF (mm)	163	344	64	114	125	565
SF:P	0.09	0.11	0.05	0.06	0.09	0.27
Q:P	0.40	0.48	0.38	0.46	0.51	0.60
Q:T	0.59	0.71	0.47	0.59	0.60	0.70
ET (mm)	1036	1570	794	1010	697	836
ET:P	0.60	0.52	0.62	0.54	0.49	0.40

P – Precipitation; I – Interception losses calculated assuming throughfall as net rainfall; T – Throughfall; OV:P – Mean overland flow coefficient; OV:T – Mean overland flow: throughfall ratio; Q – Streamflow; BF: Baseflow; SF: Stormflow; SF:Q – Stormflow to streamflow ratio; SF: P – Stormflow to precipitation ratio; Q:P – Streamflow to precipitation ratio; Q:T – Streamflow to throughfall ratio; ET: Evapotranspiration; ET:P – Evapotranspiration to precipitation ratio.

Considering the net precipitation (here assumed as throughfall) as the amount of rain that effectively reaches the soil, the difference observed between forest and eucalyptus catchments decreases since throughfall was 13% lower in the former than the latter (Table 2).

3.3. Soil saturated hydraulic conductivity (K_{sat}) and overland flow

The K_{sat} median decreases with depth in all land-uses (Fig. 5). The median under forest ranged from 61 mm h^{-1} near the surface (0.15 m depth) to 11 mm h^{-1} at 0.30 m depth, to 2 mm h^{-1} at 0.50 m depth. As in the case of forest, under eucalyptus, a similar decrease in the K_{sat} order of magnitude with depth is observed with 40 mm h^{-1} near the surface (0.15 m depth) to 31 mm h^{-1} at 0.30 m depth, to 5 mm h^{-1} at 0.50 m depth. In pasture soil, the median values ranged from 22 mm h^{-1} near the surface (0.15 m depth) to 6 mm h^{-1} at 0.30 m depth, to 0.4 mm h^{-1} at 0.50 m depth. Exploring the data to verify whether this reduction with depth in the order of magnitude is significant, the set of K_{sat} values showed the following sequence (Fig. 5 and Table 2) for forest: (0.15 m > 0.30 m > 0.50 m ~ 0.90 m); for eucalyptus: (0.15 m ~ 0.30 m > 0.50 m > 0.90 m) and for pasture: (0.15 m > 0.30 m > 0.50 m > 0.90 m). The symbol ~ was employed here to show that K_{sat} at different depths are not significant.

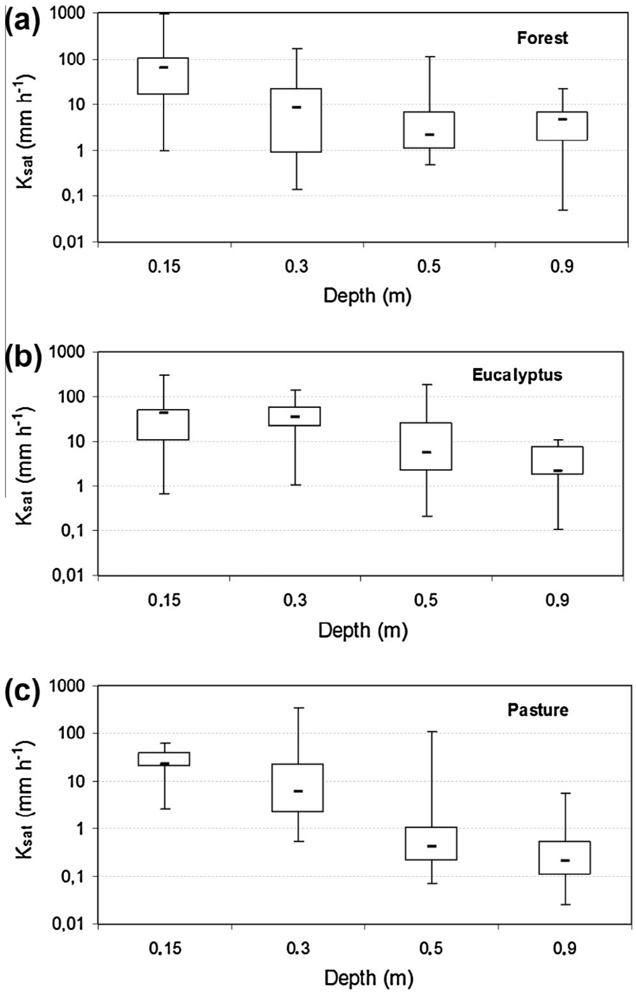

Fig. 5. Soil saturated hydraulic conductivity (K_{sat}) as a function of depth, under forest (a) eucalyptus (b) and pasture (c). The length of the box represents the sample interquartile range; the bar in the box is the median. Outlier data points more than 1.5 times the interquartile range away from the upper or lower quartile were omitted for clarity.

Although forest and eucalyptus presented the same order of magnitude regarding median K_{sat} values, K_{sat} already decreases at the shallow depth of 0.3 m in forest but only at 0.5 m in eucalyptus, even though the eucalyptus site was used as pasture 44 years ago. The comparison of K_{sat} values for each depth among land-uses showed the following sequence for 0.15 m: [forest > eucalyptus = pasture]. For 0.30 m depth, K_{sat} values show that [eucalyptus] > [pasture, forest]. For the 0.50 and 0.90 m depth, [forest ~ eucalyptus] > [pasture].

As for overland flow from the plots, in both years, the mean annual overland flow coefficients measured were very low for all catchments with the lowest mean for the forest followed by pasture and eucalyptus (Table 2). Overland flow from forest was significantly lower than pasture and eucalyptus. These, in turn, did not present significant differences.

By using shallow wells, no perched water table was observed throughout our field campaigns under all land-uses.

3.4. Streamflow

Considering the monthly streamflow in 2008, the forest presented no significant difference compared to eucalyptus (ANCOVA). The latter, in turn, had a significant lower monthly streamflow compared to pasture, which, in turn, did not differ from the forest. In 2009, the annual streamflow of the forest and pasture were significantly higher than the eucalyptus. The average 2008 wet season streamflow (average from October to March, 2008) of the eucalyptus was significantly lower than the other two catchments. The monthly streamflow of the dry season of both years was not significantly different between catchments.

The annual precipitation conversion to annual streamflow is presented here as the annual streamflow ratio (Q:P) (Table 2). The Q:P ratios for the forest and eucalyptus catchment were higher in 2009 than in 2008. Q:P ratios were lower in the forest and eucalyptus than pasture for both years (Table 2). Comparing Q:T (where T is throughfall, here assumed as the value of net precipitation) of forest and eucalyptus, the former presents higher values in both years of measurement.

The baseflow contributed much more to streamflow than stormflow for all of the catchments. The forest presented 76% of streamflow in the form of baseflow for both years. The eucalyptus had the highest proportion of baseflow contribution to the streamflow generation in the 2 years of measurement with values of approximately 87% for both years. Pasture, in turn, presented 83% and 56% for 2008 and 2009, respectively (Table 2).

Despite the differences in amount of rainfall throughout the year among the catchments, forest and eucalyptus presented more similar annual hydrographs compared to pasture (Fig. 6a–c). For the seven highest peak flows from February to April of 2009, forest and eucalyptus presented on average 13 mm of stormflow, while pasture presented approximately a threefold increase of 42 mm.

4. Discussion

4.1. Throughfall and interception

Throughfall in the forest was 67% of annual rainfall. If throughfall can be assumed to be a proxy of net precipitation, the low intensity rainfall may be one of the causes for the high rainfall interception (33%) observed in the forest (Table 2) (Fleischbein et al., 2006). The interception values found in the *Serra do Mar* in our forest site were similar to tropical montane cloud forests in Panama (37%), New Guinea (32%) and the Andean Amazon of Ecua-

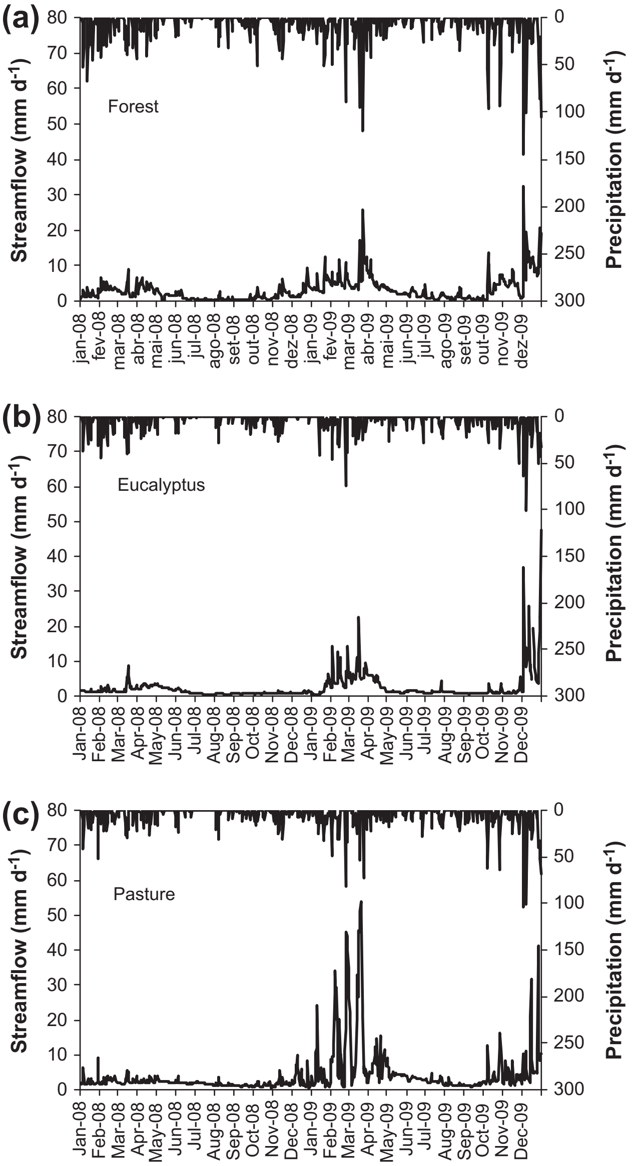

Fig. 6. Annual hydrographs for forest (a), eucalyptus (b), and pasture (c) catchments.

dor (40%) found by Cavelier et al. (1997), Edwards (1982) and Fleischbein et al. (2006) respectively.

Eucalyptus presented higher throughfall (80% of annual rainfall) compared to the forest. Assuming again throughfall as a proxy of net precipitation, the interception under eucalyptus (20%) would be 13% lower than the forest. A comparison of interception loss between Atlantic forest and eucalyptus measurements was also done by Almeida and Soares (2003). They found much higher interception for the Atlantic forest (24%) than for eucalyptus (11%). Though our interception for forest and eucalyptus (33% and 20%, respectively) differed from Almeida and Soares (2003), the difference that they found between land-use (13%) was equivalent to the one we found. Furthermore, total 2008 precipitation in the forest (1717 mm) was roughly similar to the one in 2009 in eucalyptus (1885 mm). Assuming that a comparison between years is possible as no substantial changes in rainfall intensity frequency could be noticed between these 2 years, it seems that the difference of 13% between the proportion of annual rainfall that is intercepted by eucalyptus and forest remains constant. In this point, the absence of stemflow measurements under forest and eucalyptus could have led to an overestimation of net precipitation differences. However, stemflow has been measured in a site a few kilometers from our forest site, and it was considered to be negligible (0.2% of net precipitation; Arcova et al., 2003). In the case of eucalyptus, stemflow under eucalyptus may constitute 8% of net precipitation (Crockford and Richardson, 1990). However, stemflow in eucalyptus plantations in Brazil was estimated as 3–4% of the net precipitation (Lima, 1996). Thus, unlike what would be expected by not measuring stemflow in these land-uses, these findings suggest the differences among them could be even higher had stemflow been included.

It must be pointed out that recent findings showed that a single species (i.e., palms) could have a significant influence on total stemflow in natural forests (Germer et al., 2010a). Similarly, bamboo stemflow might be significant (Onozawa et al., 2009). Both plant types are present at our forest site (Alves et al., 2010). However, our field observations showed that palms frequently do not reach the upper canopy layer. Thus, one might not expect the stemflow contribution to be as significant as they are in some parts of the Amazon (Germer et al., 2010a). This is not the case of bamboo, as our field observations as well as some studies (e.g. Lima et al., 2012) have documented that these plants frequently reach the upper canopy. Therefore, though some uncertainty is involved due the outlined points, our results show that a substantial decrease in interception loss is expected when converting forest to eucalyptus or pasture.

4.2. Soil saturated hydraulic conductivity and runoff processes

It is well known that conversion of forest to cropland in the tropics tends to increase bulk soil density, especially in the topsoil layers (Murty et al., 2002). Don et al. (2011) reviewing several studies on land conversion in the tropics found an average increase of 16% in soil bulk density between the original vegetation and the agriculture field. In turn, bulk density affects the saturated hydraulic conductivity (K_{sat}). Therefore, it is expected that forest conversion will decrease the K_{sat} in the converted land (Alegre and Cassel, 1996; Schoenholtz et al., 2000; Giertz and Diekkrueger, 2003; Martinez and Zinck, 2004; Ziegler et al., 2004; Zimmermann et al., 2006; Bonell et al., 2010).

In the present study, a significant higher K_{sat} at 0.15 m depth was observed in the forest soil compared to eucalyptus and pasture. This observation is consistent with the lowest soil bulk density found in forest soil at 0.15 m depth as well as the fact that forest soil presented the highest organic matter content which in turn increases aggregation and pore space which influences water conductivity (Neill et al., 1997; Braimoh and Vlek, 2004; Bonell, 2005; Zimmermann and Elsenbeer, 2009). These factors may explain the lowest mean overland flow coefficient for the forest compared to the other land-uses. Even when accounting for throughfall instead of rainfall in these calculations, the forest soil still presents the lowest mean overland flow: throughfall ratio (Table 2) a result consistent with those from Coelho Neto (1987) studying overland flow generation in Atlantic forest of Rio de Janeiro State.

Despite higher 0.15 m K_{sat} under forest, the median under this land-use is below the lower range found for undisturbed tropical rain forests (Table 3). For eucalyptus, our median value is similar to that found in natural eucalyptus forests that had been logged (Croke et al., 1999) and even higher than a disturbed tropical montane forest in Ecuador (Zimmermann and Elsenbeer, 2008) (Table 3). For pasture, it is situated in the middle of the range, which is close to what Zimmermann et al. (2006) found in the Amazon.

The comparison of 0.15 m K_{sat} median and 10-min rainfall intensity data (Fig. 5) may clarify the possibility of water deflection

Table 3
Median of saturated hydraulic conductivity (K_{sat}) from various studies that measured it in conditions similar to the present study.

Reference	Soil	Region	Land-use	Depth (m)	K_{sat} (mm h^{-1})	Method
Present study	Inceptisols	São Paulo/Brazil	Forest	0.15	61	Amoozemeter
			Pasture	0.15	22	
			Eucalyptus	0.15	40	
Huang et al. (1996)	Light granite soils	New South Wales// Australia	Eucalyptus – undisturbed	0	450	Disc infiltrometer
Croke et al. (1999)	Light granite soils	New South Wales/ Australia	Eucalyptus – after 5 year of harvest	0	40	Drip infiltrometer
Moraes et al. (2006)	Oxisols	Pará/Brazil	Forest	0.15	230	Guelph
			Pasture	0.15	4	
Zimmermann et al. (2006)	Ultisols	Rondonia/Brazil	Forest	0.12	130	Amoozemeter
			Pasture	0.12	22	
Zimmermann and Elsenbeer (2008)	Inceptisols	Ecuador	Forest I – disturbed	0.12	25	Amoozemeter
			Forest II – undisturbed	0.12	479	
			Pasture	0.12	3	
Majaliwa et al. (2010)	Oxisols	Uganda	Eucalyptus I	0.15	228	Falling head
			Eucalyptus II	0.15	69	
Scheffler et al. (2011)	Oxisols	Mato Grosso/Brazil	Forest	0.12	320	Amoozemeter
			Pasture	0.12	100	

to lateral flowpaths like sub-surface stormflow that might be supplemented by saturation overland flow (Godsey and Elsenbeer, 2002; Bonell et al., 2010). By doing such comparison in our catchments, a substantial generation of shallow sub-surface stormflow was not expected in any of them. Rainfall tends to be of low intensity and only exceeds the K_{sat} median value close to the surface (0.15 m) in a few events, even in pasture. For example, in both years, only approximately 0.3% of the rainfall intensities exceeded the K_{sat} median at 15 cm depth in the forest, and only 1–2% in the eucalyptus and only 3–5% in the pasture in 2008 and 2009, respectively. This result along with low overland flow coefficients may indicate the very low possibility of near-surface flowpath activation (i.e., 0.15 m or closer to the soil surface).

Considering the upper boundary of the predominant class of rainfall intensity (10 mm h^{-1}) and the K_{sat} median (Fig. 5), it is possible to infer that a perched water table would form in forest and eucalyptus at 0.50 m and in pasture at 0.30 m. However, when using shallow wells in all land-uses, no perched water table was observed throughout our field campaigns. Some explanations for this may include: (a) if sub-surface flow occurs, it may be a short duration process that could not be observed in the field campaigns (Germer et al., 2010b); (b) K_{sat} has high spatial variability and a perched water table may occur only in some places within the catchment; (c) the perched water table could be localized in shallower or deeper depths; and (d) K_{sat} might be underestimated especially with depth due to smearing and blockage of pore entry and compaction of soil walls while digging (Bagarello, 1997; Zimmermann et al., 2006).

4.3. Streamflow

Bruijnzeel (2004) showed that despite annual streamflow increase when converting tropical forest to pasture and crops, the dry season streamflow decreased in converted catchments. The increase in the annual streamflow is explained by a decrease in the evapotranspiration of the subsequent crop in relation to the original forest (Bruijnzeel, 2004). The decrease in the dry season streamflow is expected because there is generally a decrease in K_{sat} with forest conversion. Thus, during the wet season a lower amount of rainfall infiltrates into the soil, increasing stormflow and decreasing groundwater recharge, which maintains the baseflow during the dry season. On the other hand, for tropical MCFs, it was hypothesized by Zadroga (1981), cited by Bruijnzeel et al. (2011), that due to the extra water input by cloud-water interception and lower evapotranspiration of MCFs, the conversion of these forests would lead to a decrease in the streamflow despite the lower evapotranspiration of the converted land (Bruijnzeel et al., 2011). Therefore, MCF conversion would have the opposite effect compared to the conversion of lowland tropical forests in terms of annual streamflow. There are still few studies on land conversion in the tropical MCFs to test the Zadroga's hypothesis. In Costa Rica, Bruijnzeel (2006) did not detect any significant changes after conversion of tropical forest into pasture. On the other hand, two studies showed an increase in streamflow after conversion of montane tropical forests in pasture and coffee plantations in Mexico (Muñoz-Villers, 2008; Bruijnzeel et al. 2011; Ponette-González et al., 2009). Our results, in turn, indicate that when accounting for different precipitation levels (ANCOVA), we found no significant increase in monthly streamflow when comparing forest to pasture, but we found a significant reduction when comparing forest to eucalyptus in wet years like 2009.

As for stormflow generation, based on overland flow coefficients obtained from the plots, one might expect stormflow to be lower under forest compared to eucalyptus and pasture. However, the hydrograph separation results showed that stormflow is 24% of streamflow for both years in the forest and 13% of streamflow in both years for the eucalyptus. For the pasture, stormflow was 17% and 44% for 2008 and 2009, respectively. Since overland flow generation was not substantial in all catchments, these results suggest that sub-surface stormflow may be an important flowpath under all land-uses. However, by using shallow wells, no sub-surface stormflow was observed throughout our field campaigns despite the fact that we were in the field sometimes even during rainfall events. Several reasons mentioned previously may explain this lack of observation (see Section 4.2). Since shallow sub-surface stormflow was not continuously observed, its occurrence cannot be ruled out. However, it seems very unlikely that during two study years, it was never observed since we were in the field even during rainfall events. Thus, this evidence leads us to conclude that sub-surface stormflow generation might not be substantial. For this reason, we infer that the conversion of precipitation into stormflow under all land-uses to be due to the rapid infiltration and percolation of water, which in turn would raise the water table levels with the resulting stormflow to be dominated also by groundwater instead of near-surface pathways.

As pointed out by Bonell (2005), this predominance of vertical flowpaths does not mean that, for example, saturation overland flow is ruled out. It means that it can occur in valley floors, so it is a *localized* process instead of being a *widespread* process. In this respect, the fact that no significant difference was observed for dry season streamflow between our catchments might be an additional indication of no substantial generation of lateral flowpaths. Therefore, there is a predominance of vertical flowpaths irrespective of land-use.

Higher evapotranspiration rates under forested ecosystems relative to grasslands (Zhang et al., 2001) may explain differences in baseflow proportion between our catchments. This factor along with the predominance of vertical flowpaths may explain for the higher proportion of baseflow relative to stormflow in all of the catchments. As matter of fact, the pasture had higher baseflow: precipitation ratio in 2008 compared to the other land-uses. For 2009, despite being a wetter year, there was still a predominance of baseflow even in pasture but also a substantial increase in stormflow, which follows K_{sat} and rainfall intensity predictions. For example, during 2009, approximately 5% of the events exceeded K_{sat} near the surface in the pasture. This amount of rainfall represented 32% in terms of contribution to the total rainfall in our catchment. This source of lateral flowpaths as well as those generated on highly compacted cattle trails that cross the stream as described by Biggs et al. (2006) might be the reasons for the higher stormflow response in this year in the pasture compared to forest and eucalyptus (Fig. 6).

Finally, in regard to the higher streamflow: throughfall ratio (Q:T) in forest than in eucalyptus shows that throughfall conversion to streamflow is higher under forest than in eucalyptus since annual throughfall from these two sites was similar in 2008 (Table 2). One possible reason for this finding is the different evapotranspiration rates that each type of vegetation presents when under similar rainfall or, in the case of the present study, throughfall input. In this respect, the eucalyptus stand was 4–5 years old in 2008, and at this age, eucalyptus plantations are expected to present one of the highest evapotranspiration rates (Kuczera, 1987; Andréassian, 2004; Engel et al., 2005; Wood et al., 2008) depleting the soil water storage substantially compared to other land-uses (Calder et al., 1997). For instance, Calder et al. (1997) found the highest soil moisture depletion rates under eucalyptus compared to teak (*Tectona grandis*), Jackfruit (*Asterocarpus heterophyllus*), and ragi (*Eleusina coracana*) under the same soil and climatic conditions in India. These differences in soil moisture depletion, ultimately, lead to reduction in streamflow under eucalyptus compared to other types of vegetation (Scott, 2005).

5. Conclusion

This paper is the first effort toward a more complete description of the hydrological effects of land-use change in the Atlantic forest, one of the most endangered tropical forest hot spots of biodiversity in the world.

With the conversion of forest to eucalyptus or pasture, an increase in throughfall followed by an increase in lateral pathway activation occurs due to lower interception and the alteration of soil hydraulic properties, respectively. However, given the prevailing low intensity rainfall regime, the increase in lateral flowpath activation is not substantial. As was the case of the forest catchment, and unlike many studies that evaluated possible hydrological consequences of land-use change, the pasture and eucalyptus catchments still seem to be dominated by vertical flowpaths even though near-surface flowpaths were more activated in the eucalyptus and pasture. For this reason, streamflow seems to be still dominated by groundwater flow in all of the catchments. The persistence of vertical flowpaths despite land-use change is consistent with what has been predicted comparing K_{sat} and rainfall intensity in natural disturbances (landslides) in Ecuador (Zimmermann and Elsenbeer, 2008, 2009) and even man-made disturbances with land-use change from forest to pasture and soybean and pasture to soybean in Mato Grosso, Brazil (Scheffler et al., 2011).

A similar proportion of annual precipitation to annual streamflow occurs under forest and eucalyptus, with the more likely factors for these results being the high interception rates under the former and high transpiration under the latter.

Finally, cloud forest conversion to pasture in this region does not seem to decrease monthly streamflow.

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