Journal of Hydrology 499 (2013) 100–109

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

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

Luiz Felipe Salemi [a,*], Juliano Daniel Groppo [a], Rodrigo Trevisan [a], Jorge Marcos de Moraes [a,b], Silvio Frosini de Barros Ferraz [c], João Paulo Villani [d], Paulo José Duarte-Neto [e], Luiz Antonio Martinelli [a]

[a] *Centro de Energia Nuclear na Agricultura, Universidade de São Paulo, Laboratório de Ecologia Isotópica, Piracicaba, São Paulo State, Brazil*
[b] *Escola de Engenharia de Piracicaba, Piracicaba, São Paulo State, Brazil*
[c] *Escola Superior de Agricultura Luiz de Queiroz, Universidade de São Paulo, Laboratório de Hidrologia Florestal, Piracicaba, São Paulo State, Brazil*
[d] *Parque Estadual da Serra do Mar, São Luis do Paraitinga, São Paulo State, Brazil*
[e] *Departamento de Estatística e Informática, Universidade Federal Rural de Pernambuco, Recife, Pernambuco State, Brazil*

ARTICLE INFO

Article history:
Received 5 July 2012
Received in revised form 24 June 2013
Accepted 26 June 2013
Available online 3 July 2013
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief

Keywords:
Small watershed
Water cycle
Conversion
Tropical forest

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 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

* Corresponding author. Tel.: +55 (19)3429 4063.
E-mail address: piposalemi@gmail.com (L.F. Salemi).

0022-1694/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jhydrol.2013.06.049

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