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Water balance in a neotropical forest catchment of southeastern Brazil

Carlos R. Mello[a,*], Léo F. Ávila[a], Henry Lin[b,c,d], Marcela C.N.S. Terra[a], Nick A. Chappell[e]

[a] Soil and Water Engineering, Engineering Department, Federal University of Lavras, MG 37200-000, C.P. 3037, Brazil
[b] Department of Ecosystem Science and Management, College Agricultural Science, Pennsylvania State University, State College, PA, USA
[c] State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710061, China
[d] State Key Laboratory of Eco-hydraulic Engineering in Arid Area, Xi'an University of Technology, Xi'an 710048, China
[e] Lancaster Environmental Centre, Lancaster University, Lancaster, UK

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ABSTRACT

Brazilian Atlantic Forest is recognized by the UNESCO as one of the most important biosphere reserves on the planet but is threatened by extinction. The objective of this study was to analyze the main components of the water balance in an Atlantic Forest (Neotropical Forest) catchment in the Mantiqueira Range, Brazil, which is a Tropical Montane Cloud Forest. The main focuses was to analyze baseflow, evapotranspiration, soil moisture, and canopy rainfall interception to understand the hydrologic dynamics in this specially important montane forest. On average from the two studied hydrological years (2009/2010 and 2010/2011), evapotranspiration (ET), streamflow (SF), and water storage in the catchment at the end of hydrological year corresponded, respectively, to 50%, 34.8% and 15.2% of total gross precipitation (P). On average, baseflow corresponded to 73.5% of SF. The estimated potential groundwater recharge during the wet seasons was 403.8 mm (21.7% of P observed in the wet season) and 710.5 mm (28.5% of P observed in the wet season), respectively, for 2009/2010 and 2010/2011 hydrological years, showing that the catchment is able to store groundwater to provide the maintenance of the streamflow during early recessions and drought periods. Therefore, the baseflow is important in mountainous catchments in the tropical regions to provide important ecological functions, mainly as freshwater reserve.

1. Introduction

The Brazilian Atlantic Forest has been recognized by the UNESCO as one of the most important biosphere reserves on the planet due to its endemic species and hydrological relevance. This ecosystem, which originally covered 100 million hectares (16% of the country's area), now covers less than 7 million hectares, mostly restricted to the mountainous regions of Southeastern Brazil (Galindo-Leal and Câmara, 2003; Tabarelli et al., 2010). Due to human beings interventions, this kind of forest has been referred as Neotropical Forest remnant (Terra et al., 2017). Despite the environmental and ecological importance of the Neotropical Forests for the country, there are few studies detailing their hydrological functioning, especially regarding baseflow and its possible mechanisms and connections with other water balance components.

In tropical mountainous regions, the Neotropical Forest sites are known as Tropical Montane Cloud Forest (TMCF), and they are further classified in accordance with its elevation and dominant species. TMCF sites have a complex interaction between forest canopy, weather, soils, and streamflow, which has led to controversies regarding its hydrological role in tropical regions, mainly in the context of the baseflow behavior. To overcome these controversies, some studies have been carried out towards detailing the water balance elements (i.e., streamflow, canopy rainfall interception, soil moisture, evapotranspiration. and their relationships) around the world, but they are scarce in the Brazilian Atlantic Forest. In this regard, the availability of datasets based on a continuous monitoring of streamflow, weather, soil moisture, and throughfall, covering both the ascension and recession of complete hydrological years, is imperative. One of these few studies was that done by Salemi et al. (2013), which was based on meteorological and streamflow monitoring and a few rain-gauges for throughfall measurement during a hydrological year. However, neither evapotranspiration nor soil moisture were studied.

In other sites around the world, Muñoz-Villers et al. (2012) studied the water balance components of two TMCF sites in the central region of Mexico. They stated that these catchments are laid on a bedrock and saprolite interfaces with good permeability, which indicates reasonable capacity for groundwater storage along with relevant interrelationship

* Corresponding author.
E-mail address: crmello@deg.ufla.br (C.R. Mello).

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among the components of water balance. Fleischbein et al. (2005) and Fleischbein et al. (2006) also analyzed the water balance in a TMCF of the Equatorial Andes. They found that the canopy had a significant role in the protection of soils in terms of the overland flow generation, since the canopy reduces the impact of rainfall intensity over the ground, allowing greater opportunity for water infiltration. Wiekenkamp et al. (2016) studied the role of the soils in the hydrology of a forest in Germany. They concluded that soils with mature native forest have shown high porosity and pores interconnected that can generate preferential flows. These features lead to a higher infiltration capacity as well as greater natural streamflow regulation.

Muñoz-Villers et al. (2016) provided an important contribution to understanding the nature of the baseflow in a TMCF in the Central Mountainous region in Mexico. Based on hydrologic isotopic readings, they have proven that the baseflow can sustain the streamflow in a complex environment characterized by a steep topography and fractured bedrock. In the study in a TMCF site in Thailand by Hugenschmidt et al. (2014), they verified that the baseflow has presented greater predominance in relation to the overland flow. Caballero et al. (2012) studied a hydrological year in a TMCF in Central America and verified that the baseflow/streamflow ratio was approximately 80%, showing a greater predominance of the baseflow in the streamflow. All these studies demonstrated that the baseflow has been predominant in TMCF sites, especially if the native forests are preserved that can improve the soil's structure and permeability and thus favor soil-water infiltration and groundwater recharge (Ma et al., 2017; Wiekenkamp et al., 2016; Pinto et al., 2015).

Mantiqueira Range region is within the Atlantic Forest biome and was also recognized by UNESCO in 1992 as one of the most important biosphere reserves on the planet mainly because of its high-water yield capacity (Bruijnzeel et al., 2010). The region is one of the most important water sources for supplying the Metropolitan region of São Paulo (Coelho et al., 2015) and for feeding hydropower reservoirs located in the Grande river basin (Pinto et al., 2015). Its importance has been highlighted as strategic to mitigate harmful effects from persistent droughts, such as the one observed in Southeastern Brazil between 2014 and 2015 (Coelho et al., 2015). Thus, to understand the water balance in TMCF catchments in Southeastern Brazil is critical for supporting management actions to reduce the impacts of scarce freshwater resources.

Thus, the objective of this study was to reveal the intrinsic relationship between hydrology, soil, and forest in a TMCF catchment of the Mantiqueira Range, focusing on the canopy rainfall interception, evapotranspiration, soil moisture, streamflow, and groundwater recharge using the framework of the water balance. More specifically, we sought to answer two relevant concerns that request a more comprehensive understanding of the water balance: (i) is the baseflow capable of supplying water continuously over the hydrological year or it is more prone to short-term fluctuations? And (ii) does the water balance in the catchment in this region end up in positive (i.e., with surplus)?

2. Study site

2.1. Location and forest measurements

The studied TMCF is referred to as an Atlantic Forest Micro-Catchment (AFMC), which is located within a larger experimental watershed called Lavrinha Creek Watershed (LCW) in Mantiqueira Range, Minas Gerais State, southeastern Brazil (Fig. 1).

The AFMC encompasses 13.3 ha drainage area covered by a Dense Ombrophilous Forest, which is a typical physiognomy of the Atlantic Forest in the Mantiqueira Range (Oliveira Filho et al., 2006). Three forest inventories (2009, 2011, and 2012) were carried out in the AFMC by Terra et al. (2015a, 2015b). During these surveys, all trees with diameter at breast height (1.3 m aboveground; DBH) larger than 5 cm had their DBH and height measured in 12 sampling plots of 300 m^2 size each randomly distributed in the AFMC. With these data, an equation adjusted by Scolforo et al. (2008), which is specific to this forest physiognomy in Mantiqueira Range region, was used for estimating the existing biomass in the AFMC. Therefore, the average density and basal area of the forest (2185.3 trees ha^{-1} and 24.5 $m^2\,ha^{-1}$, respectively), the average canopy height (8.58 m ± 1.78), the average Leaf Area Index (LAI) (4.05 $m^2\,m^{-2}$ ± 1.20 $m^2\,m^{-2}$), and the carbon stock (39.06 t ha^{-1}) were calculated. The following tree species were identified by Terra et al. (2015a) as most representative in the AFMC: *Lamanonia ternata* Vell., *Psychotria vellosiana* Benth., *Myrsine umbellataa* Mart., *Myrcia splendens* (Sw.) DC., *Clethra scabra* Pers., *Guapira opposita* (Vell.) Mart., *Miconia sellowiana* Naudin, *Inga sessilis* (Vell.) Mart., *Alchornea triplinervia* (Spreng.) Müll. Arg. and *Miconia cinerascens* Miq.

2.2. Basic hydrologic and soil features at the AFMC

Soil saturated hydraulic conductivity (Ks) at the AFMC was estimated by Pinto et al. (2015) in their study about Inceptsols hydrological role in Mantiqueira Range region. The procedure adopted was that based on the Flume datasets, sorting fourteen consecutive hourly peak discharges in the rainy season. In this procedure, Ks is estimated by applying the Darcy's law equation. According to Pinto et al. (2015) and Libohova et al. (2018), the hydraulic gradient may be estimated by the difference elevation between the gauging station and the highest elevation of the catchment and this value is assumed being constant. This procedure can be applied if only instantaneous peak discharge values were selected during the rainy season, meaning that the soils were close to saturation. In this case, the water flows throughout the catchment in the "soil column" (Libohova et al., 2018). The derived Ks values varied from 1.3 to 23.4 mm h^{-1} in the AFMC.

Overall, the saturated zone encompasses the fractured massive rock gneiss, with good permeability of saprolite (Menezes et al., 2014). These geological features characterize the AFMC's capability for groundwater storage and transmittance. In general, the AFMC can be considered as a representative catchment located at elevations higher than 1400 m within Mantiqueira Range geomorphological domain, with soils, vegetation, topography, weather, and geology being most representative of the region.

Regarding the water table depth in a neighboring micro-catchment within the LCW, Oliveira (2014) monitored the water table level in 7 piezometers, and in the 2009–2011 period, it had varied from 0.8 to 1.6 m (Fig. 2). Thus, there are indicators that the depth of the subsurface unconsolidated geology is around 1.0–1.5 m.

The AFMC displays an average slope of 35% and altitude varying between 1475 m and 1685 m. It has the following soil-landscape characteristics: shallow to moderately deep soils (Haplic Cambisol – Inceptisols with the solum varying from 0.70 to 1.20 m), with high concentration of organic matter in the 0–0.5 m layer; the parent material being granite-gneiss (Menezes et al., 2014); topography is commonly undulating, strongly undulating or mountainous, and the basin shape is narrow, with a circularity index of 1.244.

2.3. Meteorological condition

From 2006 to 2012, the meteorological variables (precipitation, air temperature and relative humidity, atmosphere pressure, air density, dew point, wind velocity and direction, and global solar radiation) were recorded at the LCW by two standard automatic meteorological stations separated by a distance of 740 m (Fig. 1). The Köppen climate type for Mantiqueira Range is Cwb, which can be summarized as temperate highland tropical climate with dry winters and rainy summers. The mean annual observed temperature between 2006 and 2012 was 16 °C and was calculated from the hourly values recorded by the meteorological station 2 (Fig. 1). The minimum and maximum annual mean observed temperatures were 10 °C and 23 °C and were calculated by taking the minimum and maximum daily values from the same

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