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Water balance in a neotropical forest catchment of southeastern Brazil

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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

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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

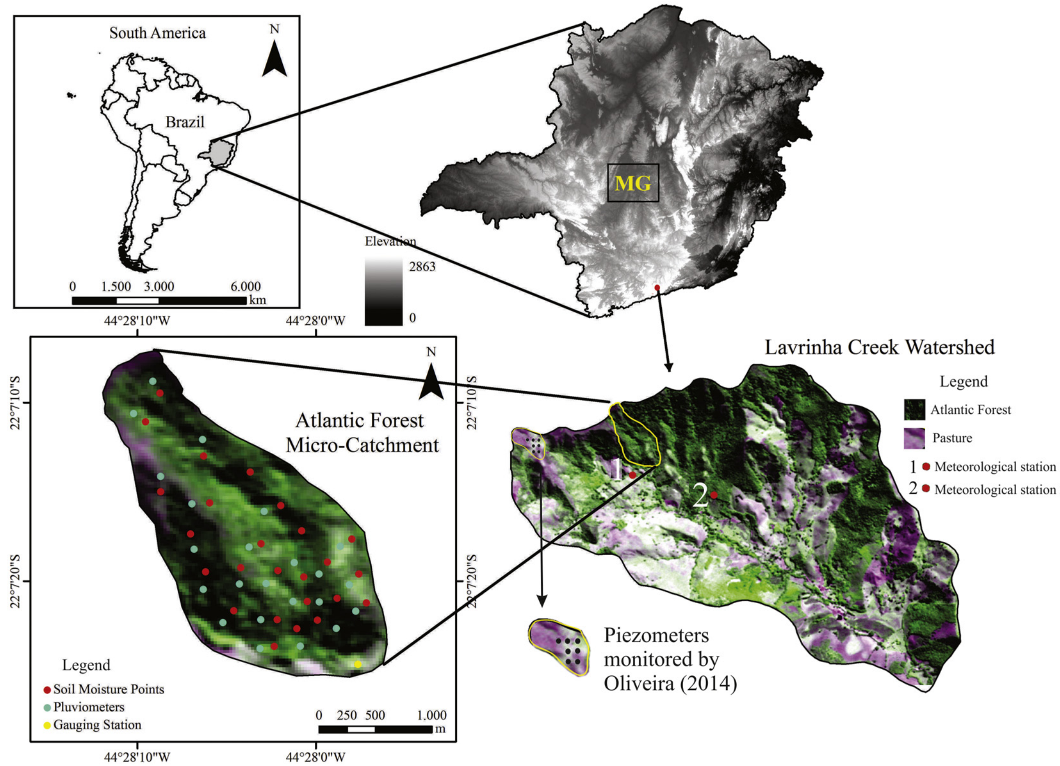

Fig. 1. Geographical location and instrumentation used for monitoring water balance elements in the AFMC, Mantiqueira Range, Minas Gerais (MG) state, southeastern Brazil.

meteorological station. From 2006 to 2012, annual precipitation ranged from 1841 mm to 2756 mm; on average, it corresponded to 2311 mm, with 89.5% of this amount concentrated between September and March. Thus, there is a marked dry period, which begins in April and ends in August and the hydrological year for the studied region is defined as the period from September in one year to August in the following year.

3. Methods

3.1. *Components of water balance at the AFMC*

The AFMC was monitored from June 2009 to December 2011, within the scope of a wider research and development project sponsored by the Minas Gerais state Electrical Energy Company (CEMIG) and the Electrical Energy National Agency (ANEEL). This monitoring effort allowed to account the elements of water balance using two complete hydrological years. The datasets encompassed canopy rainfall interception, soil moisture, weather, streamflow, and other soil and vegetative measurements carried out during the same period.

3.1.1. *Meteorological elements and evapotranspiration*

The monitoring involved meteorological variables, which were recorded by a Campbell automatic weather station (model: "WeatherHawk" station; Station 1 – Fig. 1) installed in a clear-cut area 30 m from the AFMC. It was assumed that these data sets are

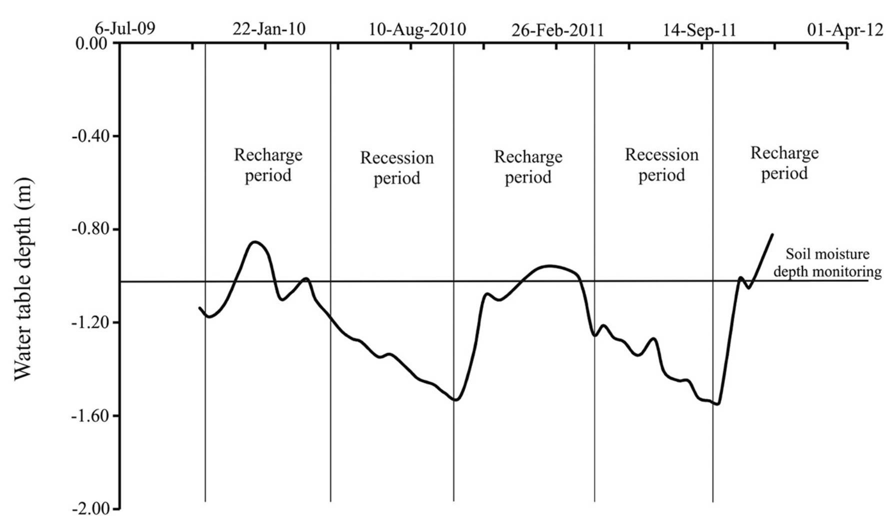

Fig. 2. Average water table depth between 2009 and 2011 in an AFMC neighboring micro-catchment also located in the Lavrinha Creek Watershed as observed by Oliveira (2014) (see the piezometers' location in Fig. 1).

representative of the conditions at 2 m above the forest canopy (Fleischbein et al., 2010; Muñoz-Villers et al., 2012; Salemi et al., 2013).

Using the observed meteorological variables and the procedures used by Allen et al. (1998), the Penman-Monteith model (Monteith, 1964) was applied to estimate daily evapotranspiration (ET, mm d^{-1}) for the studied site:

$$ET = \frac{\Delta \cdot Rn + \rho \cdot cp \cdot (es - e) \cdot g_a}{\lambda \cdot \left(\Delta + \gamma \cdot \left(1 + \left({}^{g_a}/_{g_c}\right)\right)\right)} \quad (1)$$

where Δ is the slope of the saturation vapor pressure curve (kPa °C^{-1}); λ is the latent heat of water vaporization (MJ kg^{-1}); Rn is the net radiation (MJ m^{-2} d^{-1}); ρ is the moist air density (kg m^{-3}); cp is the specific heat at a constant pressure (1.013 kJ kg^{-1} °C^{-1}); es is the saturation vapor pressure (kPa); e is the current vapor pressure (kPa); g_a is the aerodynamic conductance (m s^{-1}); g_c is the conductance of water vapor in the canopy (m s^{-1}); and γ is the psychrometric constant (kPa °C^{-1}).

It was necessary to calculate the Rn, based on latitude, altitude, leaf area index, and global solar radiation, according to the following equations (Yin et al., 2008; Allen et al., 1998):

$$Rn = Rsw + Rlw \quad (2)$$

$$Rsw = Rg \cdot (1 - \alpha) \quad (3)$$

$$Rlw = \left(\left(0.9 \cdot \frac{n}{N}\right) + 0.1\right) \cdot (-0.34 + (0.14 \cdot \sqrt{e}) \cdot K_{S-B} \cdot (T_{air} + 273)^4) \quad (4)$$

Rsw and Rlw are short and long wave radiation (MJ m^{-2} d^{-1}), respectively; Rg is the global solar radiation, which was monitored at our weather station every 60 min (MJ m^{-2} d^{-1}); α is the albedo, considered constant and equal to 0.12 for forests as assumed by Muñoz-Villers et al. (2012); $K_{S\text{-}B}$ is the Stephan-Boltzman constant (4.903 × 10^{-9} MJ K^{-4} m^{-2} d^{-1}); n is the actual duration of sunshine (hours); N is the maximum duration of sunshine (hours); and T_{air} is the air temperature (°C).

For g_a calculation, an average canopy height of 8.6 m was considered based on observed forest data in the catchment (Allen et al., 1998). The conductance of water vapor in the canopy (g_c) was obtained by:

$$g_c = g_s \cdot LAI \quad (5)$$

where g_s is the stomatal conductance, and LAI is the leaf area index (m^2 m^{-2}). The values of g_s were estimated by Pereira et al. (2010) who studied another forested site within the LCW at similar altitudes during the dry periods of 2008 and 2009.

The LAI was monitored with a LAI2000 Plant Canopy Analyzer (Licor Biosciences, Nebraska, USA) and a sensor with a viewing angle of 180 degrees. To reduce the uncertainties of the LAI measurements, a reading with a clear sky was firstly performed as a reference. Then, 10 more readings were taken, spaced approximately 10 m apart within the forest in a 20 m × 90 m area, following a straight path through the center of the area to avoid boundary effects, searching to cover the entire area. This procedure was repeated twice in a roundtrip path for 20 readings, always performed before 09:00 a.m. or after 3:00 p.m., and avoiding cloudy days, performed approximately twice a month.

A comparative analysis was carried out between the evapotranspiration modeled based on the Eqs. (1) to (5) (ET) and the evapotranspiration obtained based on the water balance method conducted during the months of the dry period (from April to August of 2010 and 2011) (ET_{WB}). This procedure implies that ET from the water balance was calculated mainly based on the changes in soil-water storage in the 0–1.0 m layer (control layer) and in observed rainfall events that normally do not have a significant impact on streamflow, mostly returning to the atmosphere by evaporation from canopy (Tomasella et al., 2008). Thus, ET can be estimated by the following water balance equation:

$$ET_{WB} = TF - \Delta S_{USZ} + C \quad (6)$$

where ET_{WB} represents the evapotranspiration from this water balance (mm), TF is the throughfall (mm), ΔS_{USZ} is the soil-water storage change in the 0–1.0 m layer (in mm) that was taken approximately every 20 days, and C is the rainfall canopy interception.

Aiming to strength the validation of the ET estimated in this study, the daily estimated values were accounted for 8-day (ET 8-day), and then were compared to the values extracted from MODIS/Terra Net Evapotranspiration 8-day with 500-m of spatial resolution, considering the two studied hydrological years (ORNL DAAC, 2018; Running and Mu, 2017). The datasets from MODIS are also estimated based on Penman-Monteith by means of an algorithm developed by Mu et al. (2007). These datasets are validated based on ground meteorological observations and Eddy Covariance flux towers around the world (Mu et al., 2007).

3.1.2. Rainfall canopy interception

Twenty-five rain-gauges for throughfall measurement (model: “Ville de Paris”, manufactured with a 415 cm^2 orifice), were installed 1.5 m above the ground across the catchment (Fig. 1). Throughfall measurements were taken at approximately noon time of each rainy day in an attempt to reduce problems with accumulation and overlap of rainfall events.

Rainfall events with less than 20 mm and separated by at least 24 h were taken to estimate the maximum canopy storage capacity (Sc) (Cuartas et al., 2007) by means of a linear regression between the average throughfall (y) and gross precipitation (x). The Sc corresponds to the x value when y = 0. For the AFMC, Sc was equal to 1.58 mm d^{-1}.

From these readings, the canopy rainfall interception (C) (mm) was determined by the following equation (Ghimire et al., 2017):

$$C = P - TF - Stf \quad (7)$$

where P is the gross precipitation (mm), TF is the throughfall (averaged from 25 gauges) (mm), and Stf is the stemflow which was not measured in this study since it is not significant from a water balance point of view (Zimmermann et al., 2013).

On computing evapotranspiration (ET) through the water balance, the interception loss (C) were added to the evapotranspiration estimated by Penman-Monteith when the canopy was not saturated (C < Sc); otherwise, when the canopy was saturated only C values were computed for ET, since under this condition, the transpiration can be negligible (Tomasella et al., 2008; Shuttleworth, 1992).

3.1.3. Soil water storage (SWS)

Twenty-five soil moisture probes (type PR2/6¨ Delta-T Devices, London, UK, accuracy 0.04 m^3 m^{-3}), calibrated according to Evett et al. (2006), were installed in the same location of the rain-gauges for measuring the volumetric soil moisture in depths of 0.10 m, 0.20 m, 0.30 m, 0.40 m, 0.6 m and 1.0 m. As this device does not make automatic reading of the soil moisture, we adopted a time interval between the readings of approximately 20 days. Soil water storage (SWS, in mm) for each date (t) and its change between consecutive readings were calculated, respectively, by:

$$SWS_t = \sum_{i=1}^{n} \left(\frac{\theta_i + \theta_{i+1}}{2} \times h\right) \quad (8)$$

$$\Delta S_{soil} = SWS(j + t) - SWS_{(t)} \quad (9)$$

where θ_i and θ_{i+1} are, respectively, the soil moisture in the depth i and in the follow depth (m^3 m^{-3}), n is the number of layers (0–0.10 m; 0.1–0.2 m; 0.20–0.30 m; 0.30–0.40 m; 0.40–0.60 m; 0.60–1.0 m), h is the layer thickness (mm) and j is the time interval. In addition, we calculated the SWS for the layers of 0–0.20 m (surface layer), 0.20–0.60 m (intermediate layer) and 0.60–1.0 m (deeper layer) for studying the statistical relationship with the streamflow components.

3.1.4. Streamflow

The streamflow in the AFMC was monitored by means of a Parshall flume and an automatic water level sensor (model WL16 Global Water Instrumentation, California, USA). The discharges were recorded at 60-min by the datalogger of the instrument. The hydrographs analyses were based on the daily discharge value. The procedure was carried out by the separation of the baseflow from the total streamflow by identification of the inflexion point in the recession limb from the baseflow and the beginning of the quickflow, here assumed to be all overland flow (Hingray et al., 2014). The baseflow follows the fundamentals of the Maillet exponential equation (Dewandel et al., 2002):

$$\frac{dQ}{dt} = -\alpha\cdot Q \tag{10}$$

$$Q_t = Q_o\cdot\exp(-\alpha\cdot\Delta t) \tag{11}$$

Q_0 is the initial flow rate ($m^3\,s^{-1}$), Q_t is the flow rate ($m^3\,s^{-1}$) at time t (daily), α (d^{-1}) is the recession coefficient, and Δt the number of days between consecutive flows.

The baseflow (BF depth) contribution to the streamflow (SF depth) was assessed using the baseflow index (BFI) (Clark et al., 2014; Muñoz-Villers and McDonnell, 2013; Caballero et al., 2012) as follows:

$$\text{BFI}(\%) = \left(\frac{\text{BF depth}}{\text{SF depth}}\right)\times 100 \tag{12}$$

In order to assess possible connections between streamflow, overland flow, and baseflow with evapotranspiration, throughfall, and SWS at three different soil layers (0–0.20 m; 0.20–0.60 m; 0.60 to 1.0 m), multiple regressions using the stepwise approach based on the Akaike Information Criterion (AIC) for the selection of independent variables were fitted. These analyzes have focused to demonstrate how the unsaturated zone can influence the streamflow in a TMCF like the AFMC.

3.2. Water balance

The daily water balance was calculated based on the following equation:

$$S_{AFMC}(i+1) = S_{AFMC\,(i)} + P_{(i)} - ET_{(i)} - SF_{(i)} \tag{13}$$

where S_{AFMC} (i) is the water storage in AFMC in i^{th} day (mm), $S_{AFMC\,(i+1)}$ is the water storage in AFMC in the following day (mm), $P_{(i)}$, $ET_{(i)}$ and $SF_{(i)}$ are, respectively, the rainfall, evapotranspiration, and streamflow in the i_{th} day; all variables in mm.

The potential groundwater recharge in AFMC (GS) was estimated based on the time interval adopted for soil moisture measurements (≈20 days). The following equation was applied:

$$GS_{(j)} = \Delta S_{AFMC(j)} - \Delta S_{soil(j)} \tag{14}$$

$\Delta S_{AFMC(j)}$, $\Delta S_{soil(j)}$ and $GS_{(j)}$ are, respectively, the water storage variation in AFMC accounted based on Eq. (13), in the soil-layer of 0–1.00 m (unsaturated zone), accounted based on Eq. (9), and potential groundwater recharge, in the j^{th} period of approximately 20 days.

The 0–1.0 m layer was considered for ΔS_{soil} measurement as the maximum observed solum depth being 1.20 m (Menezes et al., 2014) and the saturated zone of the catchment varied from 0.8 m and 1.6 m during the studied hydrological years (Fig. 2). These assumptions allowed the estimation of potential groundwater recharge that occurred during the time interval of the soil moisture readings.

4. Results

4.1. Water balance elements at the AFMC between 2009 and 2011

4.1.1. Rainfall and throughfall

Fig. 3a shows the temporal behavior of the gross precipitation (meteorological station 1 – Fig. 1) and the average throughfall and its respective standard errors (mm), calculated based on the spatial variability of the records, between 2009 and 2011. Fig. 3b presents the mean monthly precipitation and respective standard deviation for the LCW (meteorological station 2) based on the monitored period from 2006 to 2012. The observed gross precipitation for the hydrological year of 2009–2010 was 2250 mm and for the 2010–2011 hydrological year, 2756 mm.

In Table 1, it is presented the results of the studied meteorological variables split into seasons of the year. It was observed for the hydrological years of 2009/2010 and 2010/2011, C/P ratio of 21.3 and 20.5%, respectively. For the wet season of 2009–2010, it was observed 20.9% of interception, whereas for 2010/2011, this value was practically the same, 20.8%.

4.1.2. Evapotranspiration

Daily average values of ET modeled (ET) (Eq. 1) and ET from the water balance carried out during the dry periods (April – September/2010 and 2011) (ET_{WB}) (Eq. (6)) were analyzed to produce the statistical relationship presented in Fig. 4a. In addition, the ET 8-day values estimated in this study were compared to the ET 8-day extracted from MODIS Global Terrestrial Evapotranspiration Product (ORNL DAAC, 2018; Running and Mu, 2017) and the results are presented in Fig. 4 (b, c). Both validation procedures are essential for the study since ET accounts for the greatest portion of the water balance.

The ET averaged up to 50% of P in the AFMC and varied between the two hydrological years: from 1172 mm $year^{-1}$ (54.8% of P) to 1208 mm $year^{-1}$ (45.3% of P), respectively, for 2009/2010 and 2010/2011.

Leaf Area Index (LAI) throughout the monitoring period (monthly values) is presented in Fig. 5a, which varied from 2.8 to 5.2 $m^2\,m^{-2}$. Fig. 5 also shows ET (b), air temperature (c), and net radiation (d) throughout the study period for the AFMC, showing the correlated patterns of the meteorological variables and the ET.

4.1.3. Soil water storage (SWS) and streamflow

Fig. 6 presents the temporal dynamics of SWS and its respective limits calculated based on the standard deviation of the readings from the twenty five sampling points in the AFMC for the layers of 0–0.20 m, 0.20–0.60 m and 0.60–1.0 m.

The distribution of rainfall intensity and streamflow and baseflow are presented in Fig. 7 in a daily time-step. Here it is possible to observe a predominance of rainfall intensity values lower than 5 mm h^{-1}, in both hydrological years and only a few events higher than 20 mm h^{-1}. The seasonality of the rainfall is clearly transferred to the streamflow, with the highest peak discharges observed in the summer.

The baseflow index (BFI) values are presented in Table 2 for both wet and dry seasons calculated for the AFMC. In this study, the BFI was 0.77 and 0.70, respectively, for the hydrological years of 2009/2010 and 2010/2011.

Regarding the possible connections between baseflow and/or overland flow vs. soil water storage (SWS), evapotranspiration, and throughfall, stepwise multiple regressions were fitted and shown in Table 3.

4.2. Water balance

Fig. 8 shows the daily water balance at the AFMC calculated throughout the two hydrological years. Taking both Table 4 and Fig. 8, it is possible to infer about potential groundwater recharge in the catchment throughout the hydrological years. Based on the water storage in the AFMC and the changes on soil-water storage up to 1.0 m in depth (ΔS_{soil}), we estimated the potential GS by application of the Eq. (14). During the wet seasons (Oct-March), with the occurrence of rainfall, the positive changes in water storage can also be observed as well as increase in the AFMC's water storage (Fig. 8). In 2009/2010 hydrological water, a potential recharge of 403.8 mm was estimated,

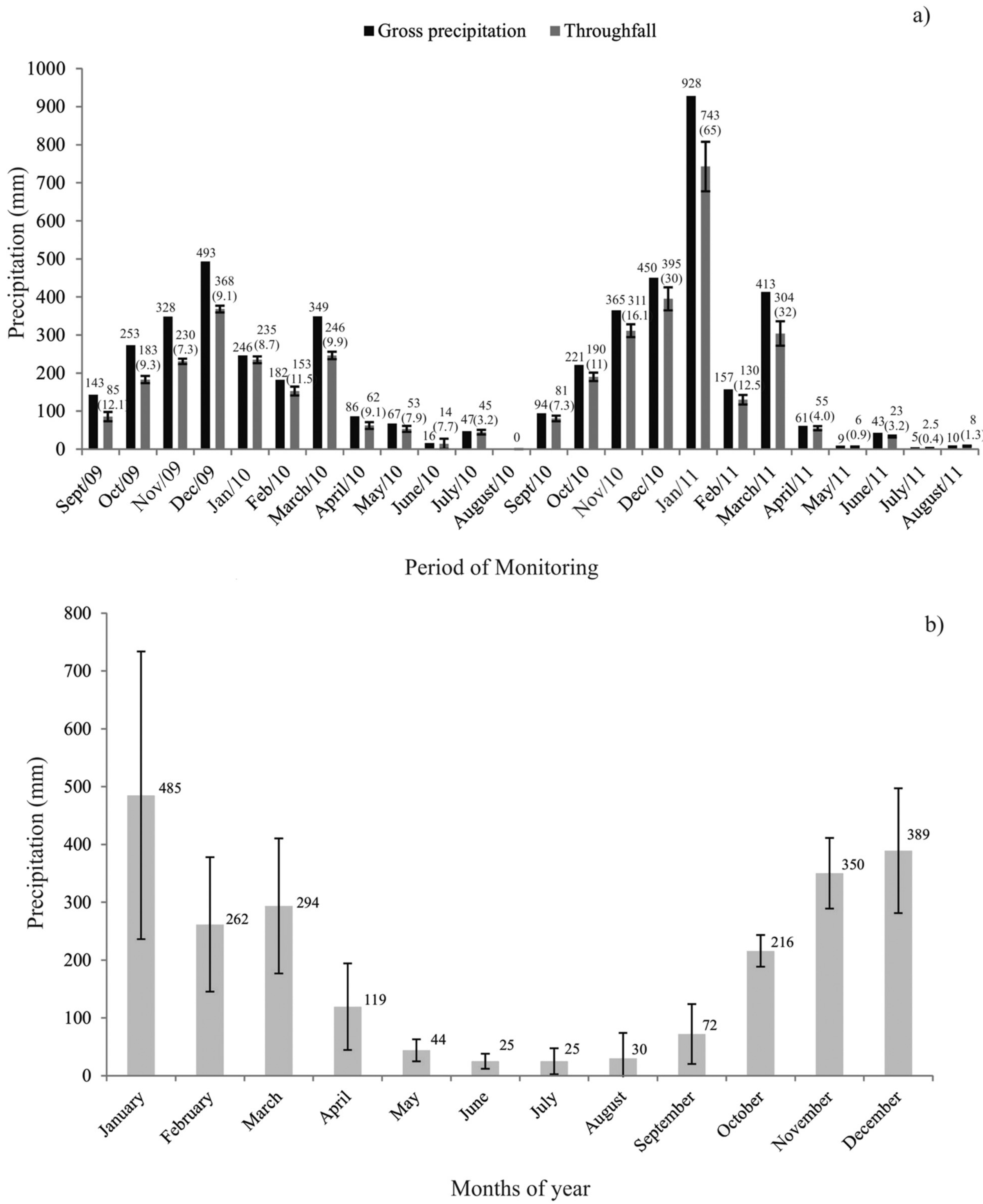

Fig. 3. Monthly gross precipitation, throughfall and its standard errors as observed in the AFMC during the hydrological years of 2009–2010 and 2010–2011 (a) and average monthly gross precipitation and respective standard deviation as observed in the Lavrinha Creek Watershed from 2006 to 2012 (b).

and for 2010/2011, 710.5 mm. In addition, a positive water storage stands out in the end of the hydrological years, with 203 mm (9.5% of P) and 554.5 mm (20.9% of P), respectively.

5. Discussion

5.1. Water balance elements at the AFMC between 2009 and 2011

5.1.1. Rainfall and throughfall

A seasonality behavior of the gross precipitation and throughfall could be highlighted in the AFMC, following the rainfall pattern of the

Table 1
Daily gross precipitation (P), canopy rainfall interception (C), and evapotranspiration (ET) for AFMC according to the seasons of the studied hydrological years.

Hydrological year	Season	P (mm d^{-1})	C (mm d^{-1}) (C/P, %)	ET (mm d^{-1})
2009–2010	Wet	10.24	2.14 (20.9)	4.84
	Dry	1.49	0.37 (24.8)	1.58
	Hydrological year	5.86	1.25 (21.3)	3.21
2010–2011	Wet	13.82	2.87 (20.8)	5.09
	Dry	0.80	0.13 (16.3)	1.53
	Hydrological year	7.31	1.50 (20.5)	3.31

region, which is characterized by a wet (summer) and a dry (winter) seasons. Comparing gross precipitation observed in the AFMC to the average value observed in the LCW (2311 mm ± 470 mm) (Fig. 3b), it can be inferred that the 2009–2010 hydrological year was closer to the expected rainfall pattern for the Mantiqueira Range region. For hydrological year of 2010/2011, the total rainfall was considerably higher than the average along with a greater concentration of rainfall in the wet season (92% of the total vs. 84% observed for 2009/2010 hydrological year). These differences can be partially attributed to an anomalous value observed in January 2011 (928 mm), which is larger than the upper boundary of the 75% inter-quartile for this month (Fig. 3b). Its occurrence was attributed to a specific weather condition that predominated over southeastern Brazil, a South Atlantic Convergence Zone episode associated with higher temperatures over the Subtropical Atlantic Ocean, which contributed with greater moisture in the atmosphere, and thus more rain for the coast of the region and surroundings (Marengo and Alves, 2012).

One of the main sources of error in gross precipitation monitoring is the wind influence, which was considered negligible due to the low annual average value in both stations (1.55 m s^{-1}). Another important source is the spatial variability due to microclimates formed in mountainous landscape and the rainfall events provoked by orographic effects. A comparison between these stations, which are separated by 740 m, demonstrated a difference of 55 mm (2.4% of the total) and 105 mm (3.8%), respectively, for the first and second hydrological years. Thus, these values demonstrate an acceptable difference for gross precipitation over LCW.

Overall, rainfall canopy interception in relation to rainfall (C/P) varied slightly between the hydrological years, with an average value of 20.9% (Table 1). In other studies conducted in TMCF sites similar results were observed, such as Ghimire et al. (2017), in Madagascar, and Muñoz-Villers et al. (2012), in Mexico. On the other hand, Salemi et al. (2013) found a C/P ratio of 33% for a TMCF site in "Serra do Mar" region, with an altitude under 1100 m. This difference is related to the species found in the site studied by Salemi et al. (2013), highlighting its larger leaves, a canopy more closed and species' morphology with greater biomass.

Standard errors related to throughfall are also depicted in Fig. 3a for the AFMC. According to Muñoz-Villers et al. (2012), the main source of uncertainty for these records is the spatial variability below the canopy. The results found here indicate that there was low variability of these data from most rain gauges, especially for the first hydrological year. This observed spatial variability for throughfall also demonstrates that the rain gauges are reasonably spatially distributed below the canopy.

5.1.2. Evapotranspiration

The ET model adopted in this study was capable of adequately estimating ET for the AFMC, supported by the meteorological data, and stomatal conductance estimated based on observed leaf area index (Fig. 5a). In Fig. 4a, it is presented the relationship between ET and ET_{WB}. The hypothesis test of the unit slope and the intercept equaling to zero showed that the fitted regression line is not significantly different from the 1:1 line (p = 0.15 and 0.41, respectively, for the angular and linear coefficients). This means that the modeled ET values were close to those calculated from the water balance conducted considering only the dry periods of the hydrological years, which was dominated by the changes in soil water storage.

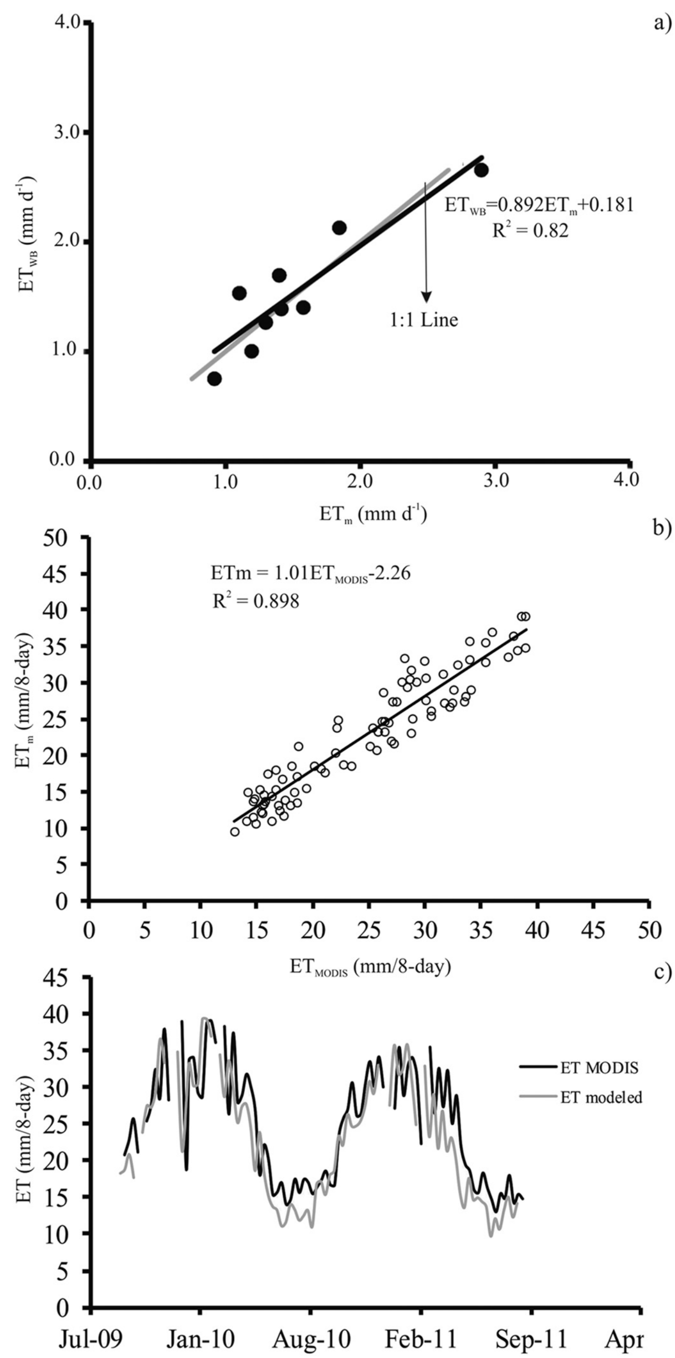

Fig. 4. Relationship between evapotranspiration modeled (ET) and evapotranspiration from water balance (ET_{WB}) during the dry periods in AFMC site (a), and comparison between ET 8-day modeled and ET 8-day from MODIS (b, c).

Fig. 4 (b, c) shows the relationship between ET modeled in the study and ET extracted from MODIS satellite for 8-day values (ET 8-day), showing a satisfactory precision of the estimates (Fig. 4b) along with an adherence between the two throughout the time (Fig. 4c). In general, ET MODIS values were slightly greater than ET modeled by approximately 8.5%.

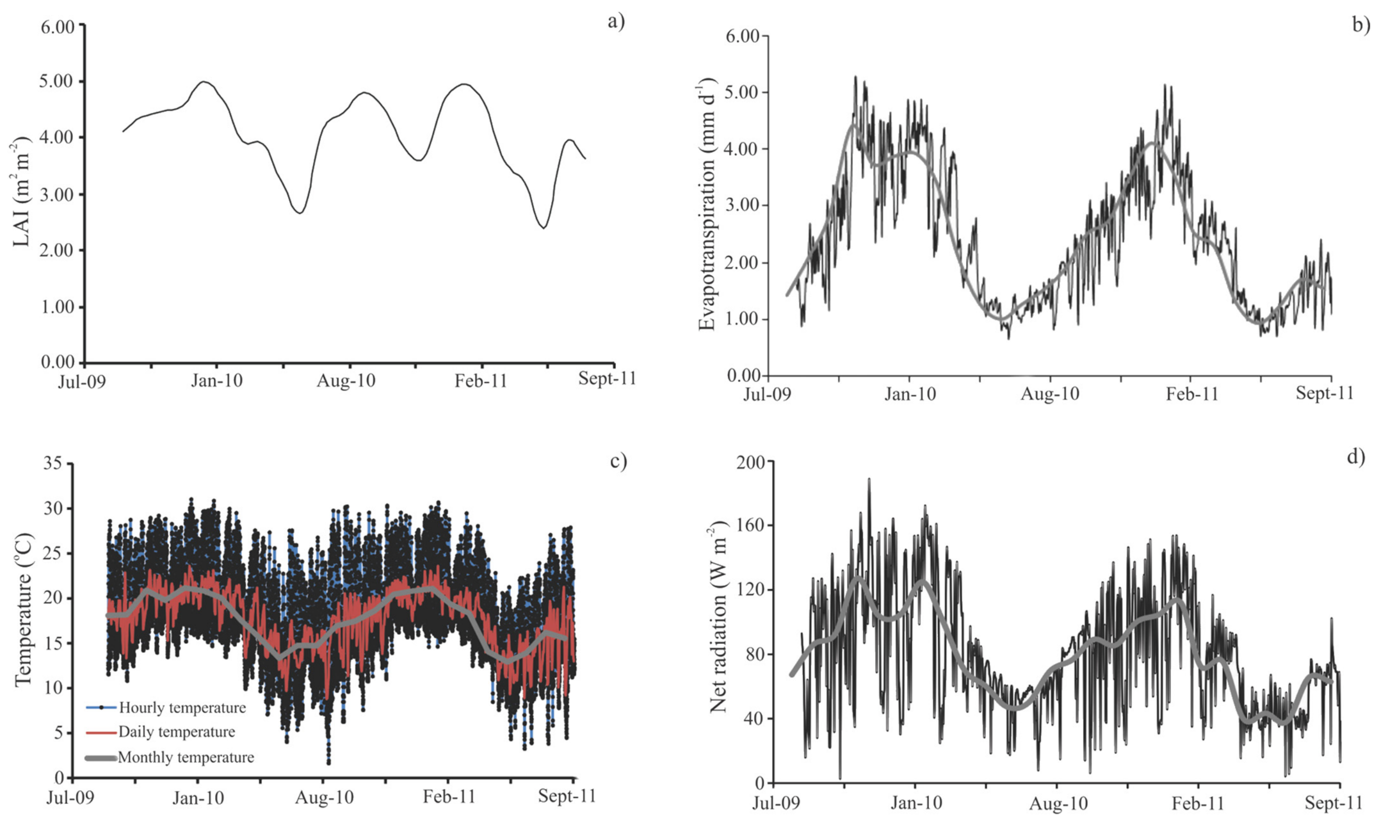

Fig. 5. Temporal behavior of the leaf area index (monthly) (a), evapotranspiration (daily and monthly values) (b), air temperature (hourly, daily and monthly values) (c), and net radiation (daily and monthly values) in the AFMC throughout the studied period (2009 to 2011).

Evapotranspiration varied slightly between the two hydrological years, which is consistent with a Dense Ombrophilous Forest, mainly due to the site being above the elevation of 1400 m. Clark et al. (2014) estimated ET values in the TMCF in the Andes region varying from 1000 to 1300 mm year^{-1}, close to those values obtained in this study. However, upon analyzing the water balance, through an approach similar to the one of this study, in two TMCF sites in Mexico, Muñoz-Villers et al. (2012) estimated ET values of approximately 790 mm for both their catchments.

For a TMCF site located in Serra do Mar, Salemi et al. (2013) found a ET/P relation of 56% during a hydrological year; however, the authors did not monitor the soil moisture, considering the variation of water storage in the catchment equal to zero in the end of the hydrological year. The ET/P ratio in the AFMC was lesser in the 2010–2011 year, similar to that value found by Zema et al. (2018), who modeled the water balance in a watershed located between 1100 and 1200 m using the AnnAGNPS model, obtained a ET/P ratio of 45%. In the case of the AFMC, this can be justified by the large number of rainy days in the period between November and March, which was associated with a saturation of the canopy and a reduction on impact of transpiration during this period. A detailed analysis of the precipitation records revealed that there were 2463 mm of rainfall during the aforementioned period. Out of the 151 days of the period, 92 (60.9%) were found to be rainy compared to only 67 (44.4%) for the same period in the 2009–2010 year. Therefore, we can state that there was a greater surplus water in the catchment available to sustain the streamflow in this hydrological year.

It is important to highlight that all the meteorological variables present a marked seasonality which is the most significant climatic feature of the region with implications for the water balance. When evaluating ET throughout the time, it is possible see that it follows the LAI, net radiation, and temperature oscillations (Fig. 5), demonstrate the importance of these meteorological variables to explain the water demand by the forest. In wet season, LAI values have oscillated around 5 m^2 m^{-2}, and the daily evapotranspiration (transpiration + wet-canopy evaporation) close to 4 mm d^{-1}. In the winter, LAI values oscillated around 3 m^2 m^{-2} while ET, 1 mm d^{-1}. These oscillations are expected for tropical and subtropical deciduous forests and occurs due to reduction in the tree physiological activities in drier and cooler periods.

Both ET and P tended to increase over the summer, indicating atmospheric conditions more favorable to both transpiration and evaporation of the rainfall intercepted by the canopy. It is important to stress that, according to Shuttleworth (1992), the participation of transpiration is greater under the conditions of a dry or moist canopy; otherwise, with a saturated canopy, evaporation is predominant. In environments like the AFMC, there is a predominance of colder and rainy weather due to its elevation (greater than 1400 m) and proximity to the Atlantic Ocean coast. Thus, in summer (wet period), the canopy moisture is close to saturation and it helps to sustain the greatest part of the atmospheric demand.

5.1.3. Soil water storage (SWS) and streamflow

Soil water storage (SWS) seasonality in the AFMC is noticeable throughout the monitoring period. In general, increasing SWS from the surface to the deeper layers and greater dynamics in the 0–0.20 m layer can be observed. Also, the deeper the layer the higher the SWS variability, which is also related to the greater influence of the forest root system in depth (mainly in the dry season). Between February/March 2011, a strong increase in SWS affected the AFMC, impacting the overland flow in the second hydrological year, which was not observed with the same magnitude in the wet season of 2009–2010.

Pinto et al. (2015) studied the role of the Inceptsols, the dominant soil type in the study area, on the LCW's hydrology based on micromorphology images and concluded that both macro-porosity and interconnections between larger pores especially at the 0–0.20 m layer

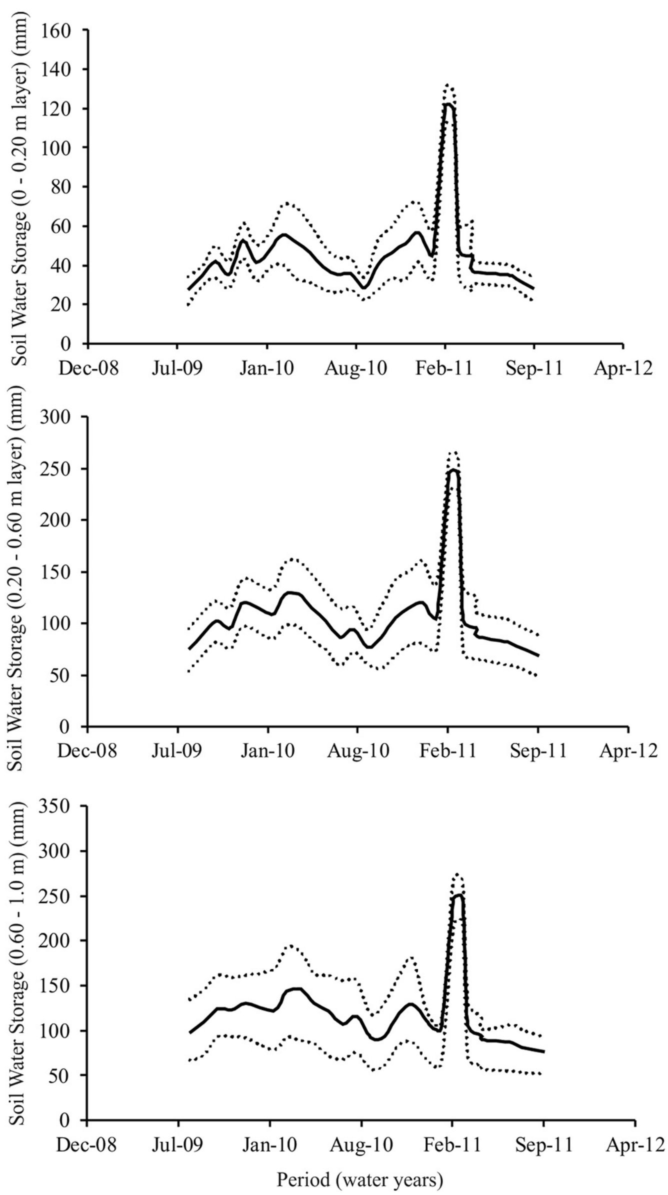

Fig. 6. Soil Water Storage dynamics (average and upper and lower limits calculated based on the 25 locations for soil moisture measurement – Fig. 1) throughout the hydrological years from 2009 to 2011.

are fundamental for infiltration capacity of these soils. It was observed that there is a clear influence of the forest on soil porosity in this surface soil layer, while in deeper soil layers there is greater micro-porosity (Pinto et al., 2015), which leads to a greater redistribution of moisture, and thus higher variability in subsoil moisture (Fig. 6 a, b, c).

Further analyzing the daily rainfall distribution and the respective streamflow in the AFMC (Fig. 7), the majority of the rainfall events has low intensity (more than 90% rainfall events were lower than 10 mm h^{-1}). The greater intensity events were observed for the 2010–2011 hydrological year. In addition, a few rainfall events with intensity greater than 50 mm h^{-1} were observed. The behavior of these rainfall events is similar to those found by Salemi et al. (2013) and have low capacity to generate overland flow, especially in a catchment entirely covered by a dense forest canopy. Examination of the SWS (Fig. 6) reveals extremely high values between January and March 2011, as a result of more than 900 mm of rain.

The BFI behavior in the AFMC was similar to that observed at other TMCF sites, with baseflow having a significant participation in the streamflow, which is particularly evident during the dry season. In these seasons, this coefficient was 0.84 and 0.89, respectively, for 2010 and 2011. Clark et al. (2014), in analyzing a hydrological year for a TMCF in the Andes with fractured bedrock, observed BFI oscillating from 0.60 in the wet season to 0.83 in the dry season. They concluded that the baseflow has been the main factor responsible for streamflow maintenance. Caballero et al. (2012), in studying a TMCF in Costa Rica, also found results similar to those of this study, with a BFI around 0.80. They concluded that the participation of the baseflow was significant because of the amount of groundwater stored throughout the rainy season. Thus, we have demonstrated that the BFI values in the AFMC are quite consistent with other studies carried out in TMCF sites around the world, including Hugenschmidt et al. (2014), Clark et al. (2014), Caballero et al. (2012), and Crespo et al. (2011) for northern Thailand, eastern Andes (southern Peru), Costa Rica (Central-America), and Equatorial Andes, respectively.

Some insights from Table 3 can be highlighted. Firstly, the correlations were significant according to the *t*-test. Stepwise regression demonstrated that the overland flow could be well explained by the throughfall and SWS at 0.20–0.60 m layer. However, for the baseflow only SWS at 0.60–1.0 m layer was significant and positively correlated. The positive correlation between overland flow and SWS at 0.20–0.60 m can be explained based on the fact that throughfall infiltrates rapidly through 0–0.20 m layer via macro-pores (Pinto et al., 2015), whose breakthrough leads to a saturation in the sub-surface layer (0.20–0.60 m) that leads to overland flow. The SWS at the deepest layer (0.60–1.0 m) presented a significant but negative correlation with overland flow; whereas for baseflow, it was significant but positive, suggesting that this layer is well connected to the baseflow. In this sense, we can infer that SWS at the 0.60–1.0 m layer played an important role in the saturated zone water storage capability in the AFMC.

5.2. *Water balance*

A marked predominance of positive water storage in the catchment in the wet seasons (2009/2010 and 2010/2011) stands out. Larger values for wet season of 2010/2011 can be observed as a result of the significant amount of rainfall observed in the region in this period. Additionally, we can also see that the AFMC is very sensitive to the rainfall occurrence, being the water balance elements on wet season more dynamic, showing a quick respond even for slight rainfall occurrence.

The results presented in Table 4 allow us to demonstrate that water storage in the AFMC has an important role for the baseflow. The capability of the AFMC for water storage during the wet season, and how the catchment deals with it throughout the hydrological years are fundamental for maintenance of the streamflow in the recession period. Muñoz-Villers et al. (2016) studied the baseflow behavior on the basis of water transit time, by means isotope hydrology in a TMCF in Mexico. They found that the resident time in the saturated zone of the catchment varied from 1.2 to 2.7 years, concluding on the possible controls of baseflow by long subsurface flow paths that are related to the permeability of the soil-bedrock interface. Clark et al. (2014) and Caballero et al. (2012), both carrying out studies in TMCF sites in Andes and Central America, respectively, observed a significant participation of the baseflow, which indicates that it sustains the streamflow throughout the dry period. Clark et al. (2014) further discussed aspects regarding the hydrogeology of the catchment, showing a considerable amount of groundwater along with possible existence of fractures in the bedrock.

Muñoz-Villers et al. (2016) characterized a TMCF site in Mexico with a soil-bedrock interface along with saturated hydraulic conductivity (Ks) varying from 1 to 15 mm h^{-1} for 65% of the catchment's area. Based on these Ks values, they characterized the transition between the saprolite and bedrock as of high permeability, favoring the groundwater storage and movement in the catchment. A similar

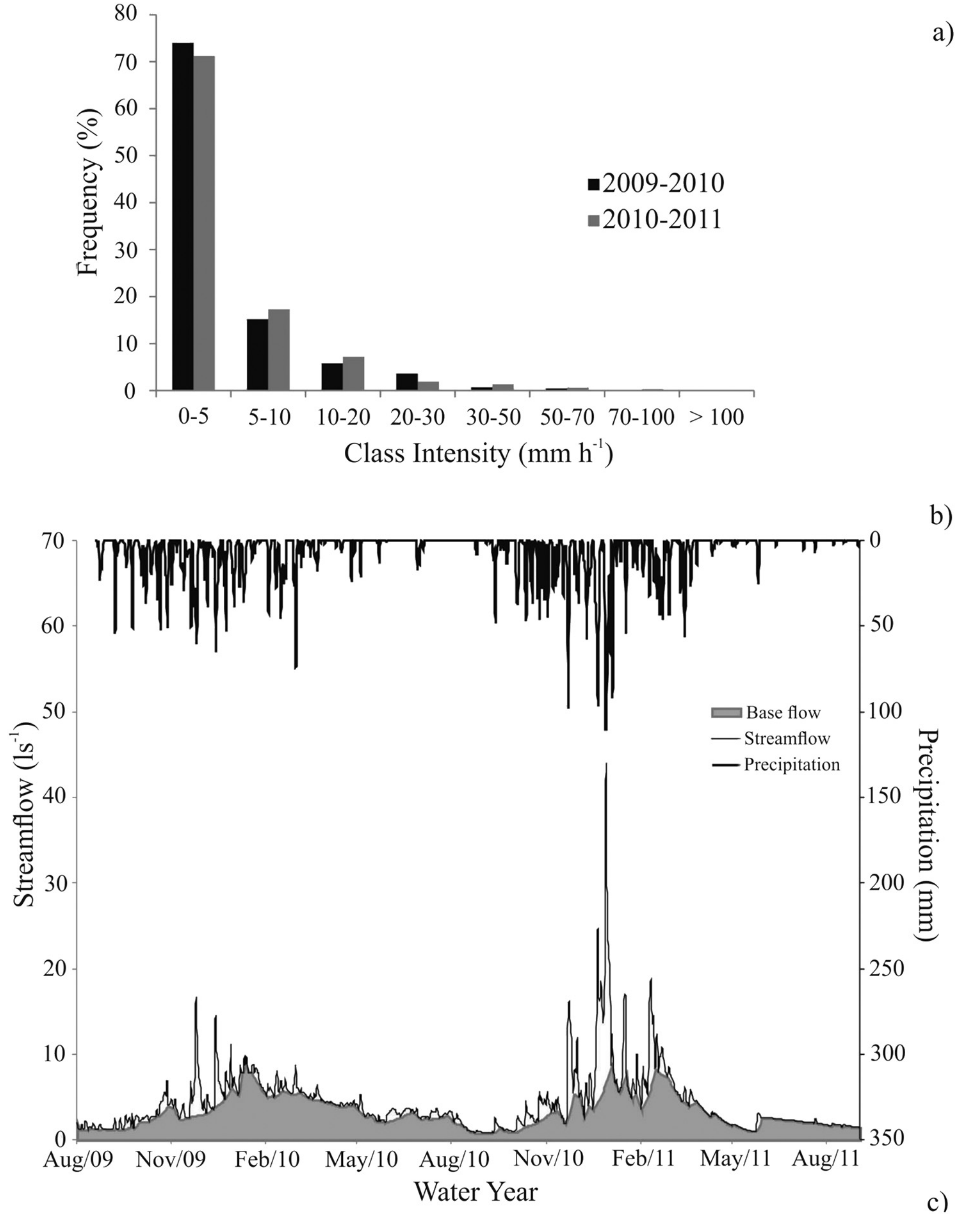

Fig. 7. Classes of rainfall intensity frequency (a) and daily streamflow, base flow and rainfall (b) throughout the hydrological years in the AFMC.

Table 2
Streamflow, baseflow, and baseflow index (BFI) coefficient for seasons of the studied hydrological years in AFMC.

Hydrological year	Season	Streamflow (mm d^{-1})	Base flow (mm d^{-1})	BFI
2009–2010	Wet season	2.86	2.10	0.74
	Dry season	1.31	1.10	0.84
	Hydrological year	2.09	1.60	0.77
2010–2011	Wet season	3.85	2.50	0.65
	Dry season	1.09	0.97	0.89
	Hydrological year	2.47	1.74	0.70

relation may be established for the studied AFMC as Ks values ranged from 1.4 to 23.7 mm h^{-1}, and fractured bedrock, colluvial deposits, and permeable saprolite are the main geological features for Mantiqueira Range region (Pinto et al., 2015). Thus, there are indications that the baseflow in the AFMC is sustained by hydrogeological functions described as of good permeability in the transition between saprolite and bedrock.

In addition, the AFMC has a narrow shape (the circularity index is 1.244), and under this condition, the hydrological connectivity between hillslopes and the drainage systems is higher than for rounded catchment shapes, which increase the frequency of water table formation (Hrachowitz et al., 2009).

Differences in the water balance elements between the two hydrological years could be noticed. The greater amount of GS estimates is linked to: (i) the total precipitation in 2010/2011 is much greater than what was observed for 2009/2010, besides more concentrated. In January/2011, it was observed more than 900 mm and a greater number of rainy days, affecting the water balance components in a different manner as compared to 2009/2010; (ii) these impacts could be observed on the greater streamflow, lower canopy interception and ET, saturation of the soil profile and thus, a larger amount of water surplus available for storage in the AFMC. Therefore, we could observe a more significant GS for the AFMC, which was reflected in a greater baseflow participation in the dry season of 2011, given by the greatest BFI observed during the studied period (0.89 – Table 2).

Some limitations need to be highlighted in this study. First of all, we

Table 3
Multiple regressions for baseflow and overland flow in the AFMC as a function of soil water storage (SWS) in different layers, evapotranspiration, and throughfall.

Hydrologic variable	Explaining variables	Estimate parameter	*p*-Value (*t*)	Ajusted-R^2
Streamflow (overland flow + baseflow)	(Intercept)	5.73593	0.7007	0.6197
	Throughfall (mm)	0.27284	3.11e-05***	
	SWS 20–60 cm	0.31514	0.00622**	
Overland flow	(Intercept)	−10.63396	0.37755	0.7077
	Throughfall (mm)	0.24029	2.25e-06***	
	SWS 20–60 cm	0.62341	0.00435**	
	SWS 60–100 cm	−0.50479	0.04583*	
Baseflow	(Intercept)	−9.8888	0.457907	0.4803
	SWS 60–100 cm	0.19736	0.011014*	
	Evapotranspiration	0.34162	0.000433***	

Note: *p*-value (*t*) means *p*-value of the *t*-test applied to the parameter: * significant at 0.05; ** significant at 0.01; *** significant at 0.001.

did not evaluate the impact of condensation on the water balance, as done by Clark et al. (2014), who demonstrated that almost 10% of the baseflow is formed by this source of water. Furthermore, similar to Clark et al. (2014), Muñoz-Villers et al. (2012), Caballero et al. (2012) and Salemi et al. (2013), deep percolation into the groundwater system was not detailed in a daily time-step and we calculated a potential recharge based on the readings of soil moisture for each 20 days (Eq. (15)). However, the existence of a great water storage capacity in the AFMC was demonstrated based on the daily water balance, which was the first study with this time resolution encompassing two complete hydrological years in this kind catchment in Brazil.

Despite the above limitations, our TMCF site is within a Biosphere Reserve recognized as one of the most important ones on the planet, mainly due to its hydrologic behavior. The datasets involved in this study bring important insights into the water balance and streamflow connections. Our findings show some important novelties: (i) the baseflow is the primary source for streamflow and it was not linked to short-term fluctuations of rainfall; (ii) we could demonstrate that the catchment can store water in the wet season aiming to maintain the permanent streamflow even in the recession phase of the hydrological year; (iii) these results can be applied to support ecological services in mountainous catchments in southeastern Brazil, giving the necessary scientific support for protection of the Atlantic Forest biome, showing its relevance in reducing harmful effects from droughts that have threatened this Brazilian region in recent years.

6. Conclusions

This study is among the first efforts to understand the water budget in a mountainous forest located above 1400 m asl in Brazil. Baseflow is found to be the main hydrological element in this catchment that maintains the streamflow, not only during the recession phase, but also for longer periods especially during prolonged droughts. The baseflow is attributed to groundwater storage capacity that has helped sustain the streamflow. Major findings of this study are summarized as follows:

a) Rainfall interception by the canopy (C) was significant and corresponded to 21.3% and 20.5% of the gross precipitation (P) in wet seasons of 2009/2010 and 2010/2011 hydrological years, respectively, with an average of 20.9% throughout the hydrological years; while evapotranspiration corresponded to an average of 50% of P, with a greater demand in the wet season of 2010/2011 due to both greater interception and the atmospheric demand;
b) Streamflow accounted for 34.8% of P, with a high predominance of

Table 4
Variation in water storage in the entire AFMC (ΔAFMC), in unsaturated zone (ΔS_{soil}), and estimated potential groundwater recharge (GS, for the end of the wet seasons) in the studied hydrological years.

Hydrological year	Season	ΔAFMC (mm)	ΔS_{soil} (mm)	GS (mm)
2009–2010	Wet season	461.3	57.5	403.8
	Dry season	−258	−88	–
	Hydrological Year	203	–	–
2010–2011	Wet season	889.6	179.1	710.5
	Dry season	−335.1	−190	–
	Hydrological year	554.5	–	–

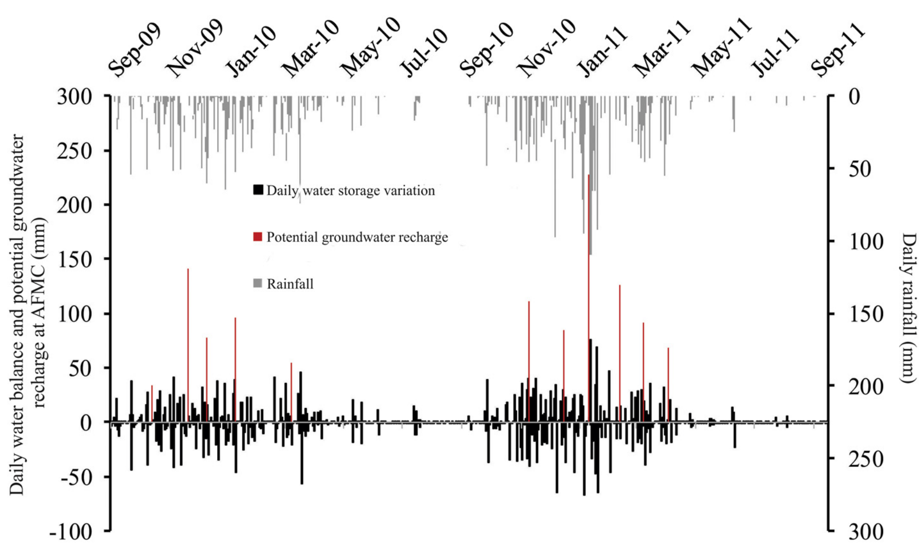

Fig. 8. Daily water balance variation, potential groundwater recharge and daily rainfall in the AFMC during the hydrological years of 2009/2010 and 2010/2011.

baseflow, being 77% and 70%, respectively, for 2009/2010 and 2010/2011 hydrological years; noteworthy was a slightly greater predominance of overland flow in the second hydrological year as compared to the first hydrological year due to greater amount and more intense rainfall events;

c) Both hydrological years closed with a positive water storage in the Atlantic Forest Micro-Catchment, corresponding to 9.5% and 20.9% of P for 2009/2010 and 2010/2011, respectively, with an average of 15.2%;
d) The predominance of water storage in the Atlantic Forest Micro-Catchment over the two hydrological years was demonstrated by means of a daily water balance, showing the resilience of this environment in terms of water yield and baseflow maintenance during dry seasons. Based on this result, the baseflow is predominant and indeed is controlled by a complex hydrogeological system, highlighting the permeability of the soil-bedrock interface that allows a significant groundwater storage in this ecosystem.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2018.09.046.

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