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Assessment of land cover change on the hydrology of a Brazilian headwater watershed using the Distributed Hydrology-Soil-Vegetation Model

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ABSTRACT

The Atlantic Forest is one of the most important forest biomes in Brazil, and this biome continues to disappear. This study looked at simulated and observed hydrological components in a small watershed containing fragments of the Atlantic Forest. The performance of the Distributed Hydrology Soil Vegetation Model (DHSVM) and the effects of possible land cover change scenarios in the Lavrinha Watershed, in the Mantiqueira Range, Minas Gerais State, Brazil, were analyzed. The model was calibrated and validated using four years of continuous hydro-climate data sets, and the simulated daily and monthly streamflow showed acceptable agreement with the observed. A comparison of hypothetical land cover change scenarios showed that deforestation in the Atlantic Forest biome leads to increases in monthly soil moisture (by 5%), overland flow (by 33%) and total runoff (by 22%), with a corresponding decrease in interception (by 71%), evapotranspiration (by 30%) and water table depth (by 10%). These changes in land surface hydrology resulted in an increase in daily high and low streamflows (by 17% and 25%), with the opposite occurring when pasture was converted to Atlantic Forest. The results also show that the hydrology of a headwater tropical watershed is characterized by seasonal variability in rainfall and land cover changes and that there are connections among the topography, land cover, soil types and wet and dry seasons that maintain the spatial distribution of the hydrologic components in the watershed.

1. Introduction

Currently, <12% of the original vegetation cover remains in the Atlantic Forest biome in Brazil, thus, both protection of remaining forest fragments and ecological restoration are crucial for the future of the Atlantic Forest (Ribeiro et al., 2009; Calmon et al., 2011). The environmental importance of the Atlantic Forest for providing biological diversity, aesthetics and recreation, fishery and wildlife products and for hydrology in general has become strategic for the sustainable development of the country. Studies of the hydrologic impacts of deforestation in the Atlantic Forest are in the initial stages in tropical headwater watersheds around the world, mainly in Brazil. It is well-established that the hydrological consequences of land cover changes are important (Maidment, 1993; Thanapakpawin et al., 2007; Mello and Silva, 2013). Reductions in forest areas can result in ecosystem soil deterioration, contributing to accelerated erosion, causing changes in the water dynamics, and a reduction in water availability (Beskow et al., 2009; Cao et al., 2011; Xu et al., 2014). Additionally, important hydrological changes may occur, associated with the decrease in interception and transpiration (Price, 2011; Salemi et al., 2013); lower infiltration rates and a deeper water table during the dry periods; increase in the runoff that may alter the streamflow patterns and hence increase storm peaks during the wet period (Brown et al., 2005).

As reported by Coelho et al. (2015) southeastern Brazil suffered the greatest drought observed in the summer of 2013/2014 and early 2015, leading to a number of impacts on water availability. In this context, Atlantic Forest could reduce the impacts from severe droughts because forest regions can provide better conditions for groundwater recharge and natural regulation of the streamflow (Menezes et al., 2009b; Price, 2011). Thus, in this type of environment, a better understanding of the land cover change and the impacts on hydrological processes in headwater watersheds can be useful for management decisions for other regional watersheds.

Simple rainfall–runoff models (lumped models) are generally dependent on empirical parameters derived using stationary time series from existing climate and land use data and are unable to predict streamflow in scenarios with climate and land cover changes outside their calibration range (Maidment, 1993; Cuartas et al., 2012). In the hydrologic response of a watershed to climate and land cover changes it is important to understand how the hydrological variables are spatially distributed in the entire watershed. It is also necessary to be able to

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link processes occurring in the atmosphere to processes occurring at the land level. These conditions are met by distributed, physically-based hydrological models.

The Distributed Hydrology Soil Vegetation Model (DHSVM), developed for mountainous regions, has been utilized in different research activities, such as: hydrologic analysis and modeling (Wigmosta et al., 1994; Beckers and Alila, 2004; Safeeq and Fares, 2012), effects of climate change on water resources (Leung and Wigmosta, 1999; Cuo et al., 2009; Dickerson-Lange and Mitchell, 2014), and prediction of future hydrologic regime resulting from changes in forest land cover (Thanapakpawin et al., 2007; Cuo et al., 2008). Due to the difficulty with the DHSVM calibration and the number of input variables and/or parameters, associated with weather, soil and plant physiology that need to be estimated or defined, the model has been used mostly in temperate climate watersheds. However, some studies have been conducted under tropical regions, highlighting the studies of Cuo et al. (2006), Thanapakpawin et al. (2007) and Cuartas et al. (2012). Thus, the model has since been applied to basins in the USA (Bowling et al., 2000), in British Columbia (Canada) (Whitaker et al., 2003; Kuraś et al., 2012), and in Asia (Cuo et al., 2006; Chu et al., 2010).

The DHSVM has been rarely employed in Brazil, despite having its source code freely available. In Brazil, this model was applied only in two basins. Kruk (2008) obtained satisfactory results in a watershed located in the Serra do Mar region (Southeastern Brazil), however the model was calibrated and verified for just four months. Cuartas et al. (2012) used the DHSVM in a smooth topographic region near Manaus (Amazon Forest region), obtaining good performance in terms of soil moisture and groundwater, but simulations of the maximum and minimum streamflows were over and under simulated, respectively. Given that the use of DHSVM has been limited in forest hydrology studies in Brazil, mainly in headwater regions, the ability of this model still needs to be tested to estimate hydrologic processes in tropical regions.

In view of the importance of quantifying the hydrologic response to land cover change in an Atlantic Forest watershed located in the most important headwater region of southeastern Brazil, the DHSVM was used in the present research. In order to understand the effects of land cover changes on the hydrology of forested headwaters in this region, the objectives of this research are: (i) to evaluate the DHSVM performance at daily and monthly time steps, and (ii) to analyze the effects of five hypothetical land use change scenarios on the hydrological cycle (streamflow, evapotranspiration, interception, total runoff, overland flow, soil moisture and water table depth variation).

2. Material and methods

2.1. Study area

The Lavrinha Watershed (LW) is located in the Mantiqueira Range region, southern Minas Gerais State, in the Upper Grande River Basin, Brazil. It has a drainage area of about 6.76 km^2, with elevations between 1137 and 1733 m (Fig. 1). The main watercourse of this small headwater watershed drains directly into the Grande River, which is one of the most important Brazilian rivers for hydroelectric energy generation (Viola et al., 2014). The LW was chosen for monitoring in order to study the hydrology and weather of the Mantiqueira Range region. The LW can be considered representative of the Mantiqueira Range region in terms of the geomorphology, climate, pedology and land uses in general. This Research & Development Project (R&D 176) was sponsored by the Minas Gerais State Electric Energy Company and the Brazilian National Electric Energy Agency (CEMIG/ANEEL).

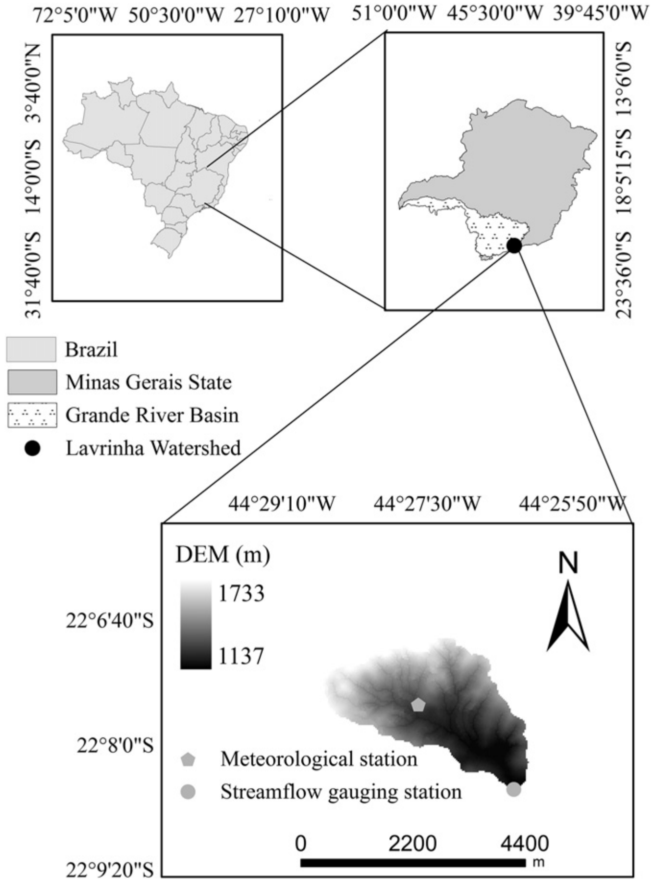

Fig. 1. Geographical location of the Lavrinha Watershed (LW) between 22° 06′ 40″ S and 22° 09′ 20″ S latitude and 44° 29′ 10″ W and 44° 25′ 50″ W longitude and the respective DEM.

According to Mello et al. (2012), the climate in this region is temperate with rainy and mild summers and dry and cold winters (Cwb according to Köppen's classification system). The average annual temperature between 2005 and 2010 was 17 °C and annual average rainfall was 2045 mm, the rainy season being between October and March, and the driest months from April to September (Fig. 2). This region is frequently affected by heavy rainfall in summer (December, January and February), and these events are mostly associated with two types of atmospheric disturbances: Cold Front (53%) and the South Atlantic Convergence Zone (47%) (Lima et al., 2010).

2.2. The Distributed Hydrology Soil Vegetation Model (DHSVM)

The DHSVM was used to simulate the hydrologic responses in LW because the model is one of the most advanced distributed hydrologic models available for simulating the impacts from different land covers in mountainous terrain and has been little applied under Brazilian conditions (e.g. Cuartas, 2008; Kruk, 2008; Cuartas et al., 2012). DHSVM is a fully distributed, physically-based model that simulates energy and water balance in each grid cell in a Digital Elevation Model (DEM) of a given watershed. The version employed in this study was 3.1.2 with the last update in March 2014.

The DEM is used to determine topographic controls on incoming shortwave radiation, precipitation, air temperature, and downslope water movement (Whitaker et al., 2003). DHSVM was originally designed for application in temperate mountainous forested watersheds located in the Northwestern USA. Basically, the model accounts for topographic and vegetation effects in each grid cell and represents physical processes such as the land surface energy balance, unsaturated soil moisture movement, saturation overland flow, snow accumulation and melt and water table recharge and streamflow. DHSVM uses a two-layer canopy representation for evapotranspiration, which is estimated by the Penman–Monteith equation. DHSVM also includes a two-layer energy-balance model for snow accumulation and melt. The multi-layer soil column in each pixel is a series of soil moisture reservoirs, and lateral saturated subsurface flow takes place from the deepest